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Final Report

MODERN SPARK TRANSMITTER TECHNIQUES

By: L. T. DOLPHIN, JR.   A. F. WICKERSHAM, JR.

Prepared for:

OFFICE OF NAVAL RESEARCH
WASHINGTON, D.C.
AND
ADVANCED RESEARCH PROJECTS AGENCY
WASHINGTON, D.C.

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ABSTRACT

This final report describes modern spark transmitter techniques, covering such areas as ring spark transmitter design, radiation patterns, experimentation, and possible applications of the ring spark transmitter. Synchronization of spark gap discharges is described, as is an investigation into spark gap pressurization. The report presents results of the study and indicates possible areas of development of the ring spark transmitter as a practical device for the generation of very high peak power in the high-frequency range.

I INTRODUCTION

Before vacuum tubes were invented, early radio experimenters succeeded in generating useful amounts of radio-frequency power by spark and arc techniques. Although Hertz succeeded in generating radiation at microwave frequencies, practical applications of spark transmitters were limited to frequencies below several megacycles. When vacuum tubes were invented the entire industry abandoned the spark transmitter to steamship emergency rooms and laboratory cellars, and many of the novel schemes suggested during spark days were never carried further.

At the present time, however, vacuum tubes are being pushed to higher power levels only at great expense and effort. Vacuum tubes are inherently inefficient, high-impedance devices. Care and cleanliness in assembling and outgassing are important. When power levels are raised it becomes a major problem to supply adequate filament emission, to cool the tube, and to guard against gas bursts, flashover, and parasitic oscillations. At the present time peak power levels of most transmitting tubes are limited to a few megawatts, with power advancements no longer measured in orders of magnitude but in a few decibels. The demand for higher peak powers, particularly for radar applications, continues to motivate research into higher power tubes, and to prompt investigation into other RF generating techniques.

A non-vacuum tube device which holds great promise as a means of generating very high peak powers was proposed in 1960 by Professor K. Landecker and co-workers at the University of New England, Australia. This transmitter is similar in principle to a Marx impulse generator in that capacitors are charged in parallel and discharged in series. Figure 1* shows a schematic diagram of a Marx impulse generator. The resulting high-voltage pulse discharges through the distributed inductance

*Illustrations appear at the end of the report.

and transient oscillations are excited. The entire system is arranged in the form of a ring. The ring serves as a magnetic dipole of fractional diameter-to-wavelength ratio, from which RF energy is radiated. Because large amounts of energy can be readily stored in capacitors, and because the capacitors are discharged in series, extremely high peak powers--tens or hundreds of megawatts--can be generated.

The ring transmitter makes use of spark gaps as switching devices to connect the individual capacitors, and the associated inductances and resistance, in series around the ring. Hence the transmitter proposed by Landecker is called a "ring spark transmitter." The spark gaps in the ring are a simple form of switching; but other switches--thyratrons, ignitrons, gas tubes, or semiconductors--can be used. Figure 2 shows a schematic diagram of the Landecker ring spark transmitter in its elementary configuration.

Some of the features of the Landecker method of generating high power levels have been presented in Landecker's article[1] and in two previous reports[2,3] published under this contract. The present report summarizes 18 months of investigation of ring spark transmitters. A number of techniques have been tried in this research program in order to physically realize the theoretical possibilities of the ring transmitter. Successful operation of a 24-Mc transmitter has been demonstrated, and the next section of this report is a brief summary of the design of ring transmitters. This should enable other workers to duplicate our results.

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[1] K. Landecker and K. S. Imrie, "A Novel Type of High Power Pulse Transmitter," Australian Journal of Physics, Vol. 13, p. 638 (1960).

[2] L. T. Dolphin, Jr., A. F. Wickersham, Jr., and F. E. Firth, "An Investigation of the Application of Modern Spark Gap Techniques to High-Power Transmitter Design," Tech. Summary Report 1, Contract Nonr 4178(00), ARPA Order No. 463, SRI Project 4548, Stanford Research Institute, Menlo Park, California (January 1964).

[3] L. T. Dolphin, Jr. and A. F. Wickersham, Jr., "An Investigation of the Application of Modern Spark Gap Techniques to High-Power Transmitter Design," Tech. Summary Report 2, Contract Nonr 4178(00), ARPA Order No. 463, SRI Project 4548, Stanford Research Institute, Menlo Park, California (June 1964).

II DESIGN OF RING TRANSMITTERS

The design of a ring spark transmitter, using the techniques developed so far, is an iterative process based on the elementary theory of an oscillating circuit and the properties of a magnetic loop antenna. For convenience, the equations derived by Landecker[1] are summarized here in a series of tables and graphs.

It is assumed that operating frequency, pulse width, and power level are known. The first step in design is to determine the Q factor which is related to angular frequency, ω, and pulse width, τ, by $\tau = 2.30Q/\omega$ seconds.

The pulse width given by this formula is calculated from the onset of the pulse to the point where the power level has fallen to 10 percent of its initial value. If the pulse length were calculated to the 1-percent decay point, the result would be $\tau = 4.61Q/\omega$ seconds. Figure 3 shows typical pulse widths for various frequencies.

The power transmitted per pulse is related to energy storage by $P = \frac{1}{2}NCV^2\frac{\omega}{2.3Q}$. Considerable variation is permitted in the selection of N, C, and V. In general, we prefer a high value of applied voltage, V, of 20 kv to perhaps 200 kv. The more capacitors in the ring, the greater the energy storage and the larger the capacitance, C_i, of the individual units, since the ring requires a net tuning capacitance of $C_i/N = C_o$.

After the number of capacitors in the ring has been determined, the net tuning capacitance $C_o = C_i/N$ can be calculated. This fixes the ring inductance, L_o, which is formed from

$$\omega = \frac{1}{\sqrt{L_oC_o}} \quad .$$

A reactance chart is shown in Fig. 4.

The net reactance, $X = \omega L_o = \frac{1}{\omega C_o}$, and the radiation resistance, $R^* = \frac{X}{Q}$, now can be determined. Next, the ring diameter, D, and current path diameter, d, can be found from the graphs shown in Figs. 5 through 8. Several recalculations of all parameters usually are necessary to obtain a realizable design. After the ring size has been determined, suitable dielectric material for the capacitors can be chosen. Some iterative recalculation may be necessary because of the effects of capacitor size and post diameter on the current path diameter.

The quality of the dielectric material used for the capacitors must be greater than the Q of the ring, or the losses in the capacitors will be excessive and efficient performance will not be obtained. The breakdown strength of the dielectric should be as high as possible, permitting the use of thin plates of small area. The effective current path diameter (Fig. 9) will be somewhat larger than the diameter of the posts which connect the capacitors to the spark gaps. This effect derives from the currents flowing in the dielectric. If the space around the ring is well-filled with capacitors, the effective current path diameter will be closer to the capacitor plate diameter than to the post diameter; thus, "d" should be an estimated mean diameter appropriate to a given design.

The capacitors are charged and isolated from one another through charging resistors. These resistors may be of 1 to 100 megohms. The product of the charging resistance and capacitance of each capacitor gives the charging time and so determines maximum pulse-repetition frequency (PRF). To allow the PRF to be adjustable over wide limits, the charging resistors should be small. Variable resistance units can be placed in the common power supply lead to vary the PRF (Fig. 10). RF chokes, rather than charging resistances, can be used in the ring; however, they must be able to withstand high voltages. Unfortunately, the chokes may be transiently excited and generate spurious radiation.

The foregoing discussion applies to the elementary form of the ring transmitter without secondary circuit. The design of suitable secondary rings, which stretch the pulse, is described in another discussion.[3]

Application of the basic techniques to other antenna configurations is straightforward. The practical limits and the possibilities of the transmitter can be seen in few example design problems.

III RADIATION PATTERNS OF RING SPARK TRANSMITTERS

This section summarizes briefly the radiation characteristics of the ring spark transmitter.

The theory of loop antennas, developed in the 1920's, is not directly applicable to the ring transmitter. The ordinary loop antenna is open at one point, the point of excitation, and is usually excited in a balanced manner. A well-known exception is the single-turn helix, which is excited at one end from an unbalanced line and a ground plane. In either case, a sinusoidal distribution of phase is developed along the perimeter of the loop, influencing the form of the radiation pattern.

The ring transmitter is excited at many points of its circumference; the 20 Mc working model, for example, may be considered excited at 67 equally-spaced points by 67 in-phase oscillators. Since the distance between excitation points is small compared to a wavelength, the phase distribution, around the ring, may be taken to be constant. This is a condition that holds for ordinary loop antennas only when the diameter is much smaller than a wavelength; thus, only in such special case will the ring transmitter radiation pattern resemble that of the ordinary loop.

For operating wavelengths of the same order of size as the ring diameter, the radiation patterns must be calculated for a constant phase distribution. We have done this in scalar approximation, and the results are shown in Fig. 11 for various ratios of diameter to wavelength, d/λ. The patterns are shown in the H-plane, a plane perpendicular to the plane of the loop and containing the loop axis. The E-plane patterns remain omnidirectional.

IV EARLY EXPERIMENTS WITH A 24-MC RING TRANSMITTER

As a result of early experiments with ring transmitters, a test-bed transmitter was constructed in mid-1963. A photograph of this device is shown in Fig. 12. Operating characteristics are shown in Table I.

The secondary ring (Fig. 13) is employed to stretch the pulse length. This ring is magnetically coupled to the primary ring and adjusted for critical coupling.

In early experiments with this test-bed transmitter, we found that power output was only a few kilowatts, about three orders of magnitude below the expected level. Weak radar returns from nearby mountains and aircraft were obtained, but both the echo intensity and field strength of the transmitted pulse were much lower than expected.

Measurements of the resistance of the 67 spark gaps in this transmitter indicated that as much as an order of magnitude of power loss could be due to ohmic losses in the gaps. The remaining loss was evidently due to the finite avalanche time of each gap. Figure 14 shows one model for the breakdown of a spark gap. A finite time, typically tens of nanoseconds, must elapse before a low-resistance spark channel is formed--unless the gap is heavily overvoltaged and triggered by a flash of ultraviolet light. Figure 15 illustrates the effect of one or more gaps firing earlier than the remaining gaps. The initial redistribution of charge before all gaps are fired can result in a loss of power of two orders of magnitude.

The use of pressurized spark gaps makes it possible to use narrower gap spacings for a given charging potential. The shorter, thicker spark has lower inductance and resistance; thus, since the spacing is smaller, the spark avalanche is completed in a shorter period of time. The use of high-pressure gaps greatly increases transmitted power.

Table I

CHARACTERISTICS OF 24-MC RING TRANSMITTER

Primary Ring

Number of Capacitors, N	67
Unit Capacitance, C_i	356 ± 1 PRF
Ring Diameter, D	0.19 λ = 112 inches
Net Tuning Capacitance, C_i/N	5.27 pf
Net Inductance of Ring, L_o	12 μh
Radiation Resistance, R*	23.3 ohms
Reactance, $X_L = X_C =$	1510 ohms
Q Factor	65
Pulse Width to 10% Power Point, τ	1.0 μsec
Peak Power, First Half RF Cycle	640 Mw (at 50 kv)
Peak Power During Pulse	17 Mw (at 50 kv)
Operating Voltage	10-150 kv

Secondary Ring

Critical Coupling, k_c	0.01
Desired Mutual Inductance, M	0.09 μh
Number of Capacitors, N	40
Unit Capacitance, C_i	356 ± 1 pf
Diameter, D	0.126 λ = 74 inches
Q Factor	200
Net Capacitance, C_i/N	8.9 pf
Total Inductance, L_o	7.1 μh
Radiation Resistance, R*	4.66 ohms
Reactance, $X_L = X_C =$	920 ohms

V CW OR LONG-PULSE OPERATION OF THE RING TRANSMITTER

Landecker and co-workers have suggested replacing the multiplicity of spark gaps with a single, central gap which is connected to the ring by N half-wave transmission lines. The difficulty with such scheme is that the impedance of the single, central gap must be very low (milliohms) in order to keep the radiation resistance of the ring as the principal source of damping. Our experiments with transmission lines have shown adjustment of the length the transmission lines is critical, and that a low-impedance central spark gap is difficult to achieve.

The use of transmission lines--to correct the ring oscillator units to a central point--opens the possibility of operating the Landecker ring as a CW transmitter. What would be required at the central junction of transmission lines is a high-speed plasma switch. In Fig. 16, we show how such a switch could be used. High-speed switches, capable of handling large peak powers, would permit CW or long-pulse operation. The spark gaps, however, cannot be replaced by thyratrons because of the slow recovery times of thyratrons and similar devices. Operating the spark gap ring in a CW mode would require a switch capable of recharging the ring at a rate equal to or slightly less than the RF frequency.

A device referred to as a plasma switch was proposed, for the purpose of achieving CW operation with a ring transmitter, in a document* describing improvements to Australian Patent #233,302. The switch consists of a glass envelope evacuated to a pressure of 1 to 60 microns. The envelope encloses two sets of electrodes and there may be a third set of starter electrodes. Potentials of 2 to 10 kv are impressed across the electrodes. The proposed mode of operation is as follows. A starting discharge across the smaller electrode produces a shock wave which travels down the tube toward the two pairs of electrodes. On

*K. Landecker (private communication).

arrival, the shock wave causes a discharge across the electrodes. Each new discharge, in turn, generates a shock wave which propagates to the opposite electrode. Thus, the plasma switch is an oscillating, non-linear, circuit element with a period of oscillation determined by the separation of the electrodes, the propagation velocity of the shock wave, and the avalanche time at an electrode. The crux of the proposed device is the pressure at which the tube is supposed to operate. It is necessary, at the operating pressure, that a discharge not be sustained by the electrodes except when a passing shock wave increases the local charge density.

An important consideration in the design of the plasma switch is the location of the return-current leads from the upper electrodes. These leads are split into two parts, and the two halves partly encircle either side of the tube, thus forming back-straps for the purpose of magnetically accelerating the plasma shocks. The Lorentz force derived from currents through the back-straps accelerates the plasma shock towards the opposite electrode.

Several models of the plasma switch were built and tested at this laboratory. A photograph of one of the first models is shown in Fig. 17. Although many voltages, pressures, and external circuits were tested, we were unable to operate these plasma switches successfully. Subsequently, several different working models were constructed to test the effects of cylindrical geometry (Fig. 18), shielding of ultraviolet flashes, and removal of the starting electrodes to large distances from the operating electrodes (Fig. 19). In all cases successful operation was not achieved. We also attempted to construct a linear plasma tube, comprising multiple electrodes, for the purpose of achieving a fast, single-pulse type of operation (Fig. 20). This device also was not successful.

It is our conclusion that the difficulties common to all of the plasma-switch devices are the thickness and propagation speed of the ionizing part of the shock waves. The thickness of an ionization wave is roughly 5 inches. The thickness, and the speed of propagation, which is of the order of 1 cm/μsec preclude operation with switching times, or frequencies, greater than tens or hundreds of kilocycles.

During our study of plasma switches, we considered the possibility of using the hydromagnetic capacitor as a circuit element. In discussions with Wulf Kunkel and William Baker, inventors of the hydromagnetic capacitor, we learned that the device has the following limitations. Since the dielectric constant of the hydromagnetic capacitor is proportional to the number density of the charge in its plasma, we can expect the frequency of an oscillator derived from a hydromagnetic capacitor to be variable and difficult to control. This follows because the charge density in a plasma varies during a discharge. Since the hydromagnetic capacitor is a coaxial device, the time required to charge and discharge it is approximately the ratio of its length to the Alfvén velocity. An additional condition of operation is that the angular frequency be large compared to the ion gyrofrequency. Combining these two conditions, we find that a 30-Mc oscillator would require a hydromagnetic capacitor with dimensions of the order of a few centimeters and would require a bias magnetic field greater than 50 kilogauss. So small a device would have the difficulties of high voltage breakdown across its insulation and excessive viscous damping between the rotating plasma and the walls of the container. For these reasons no experiments were attempted.

We learned that the inventors of the hydromagnetic capacitor encountered interference with a patent application on a similar device by H. Alfvén. The inventors mentioned that in Alfvén's disclosure there was included a scheme in which additional magnetic bias fields were used to generate radio-frequency power. To the present time, we have not obtained additional information on this scheme.

From our experiments with plasma switch tubes we conclude that development of a practical switch is a major research problem. The availability of such a tube would make it possible to extend the ring transmitter to long pulse and CW operation at extremely high powers. Developments in plasma tube work should be monitored from time to time, since new ideas eventually may permit such a device to be built.

VI RING TRANSMITTER RADIATION EXPERIMENTS

The ring transmitter is basically a magnetic dipole radiator, but its usefulness can be extended by using it to excite additional antenna structures. In order to test this possibility, and also to determine the coherency of radiation from the ring transmitter, we used a small 470-Mc (UHF) spark ring as the exciting element in a Yagi array. The small UHF ring transmitter, shown in Fig. 21, was mounted coplanar with the passive director and reflector elements of the array. In Fig. 22, we show the spacings and dimensions of the four director and two reflector elements. Figure 23 is a photograph of the array taken during the course of radiation pattern measurements. The radiation pattern measurements are shown in Fig. 24.

From the pattern measurements we conclude that there is no difficulty in coupling a spark transmitter into a unidirectional end-fire array. Inefficiencies appear to be those in the transmitter itself, not in the array performance. From the pattern measurements we can conclude also that the portion of the coherent power spectrum close enough to 470 Mc to be directed by the five-element array contains about 13 percent of the total RF power. Since frequencies within ±30 percent of 470 Mc would be directed by the array, not more than 13 percent of the total coherent radio power is contained in the 330 to 610 Mc frequency interval.

There is some indication that the radiation coherency of the 470-Mc ring transmitter is perhaps worse than the limit estimated above. Prior to construction of the array, several radiation measurements were made of the ring transmitter itself and it was observed that radiation power in the axial direction was only a few decibels less than the power in radial directions. Ordinarily, a closed loop antenna cannot be excited in an axial mode. However, by breaking the loop and exciting it at one end, a phase distribution can be achieved that gives axial radiation. Since the ring transmitter appeared to be excited in both modes, we concluded that the phase distribution was random and could, therefore, give rise to radiation in all directions. As a result of these measurements, we decided that a basic difficulty of the ring transmitter is its lack of coherency which, in turn, probably derives from a lack of precise synchronization of the discharges in the spark gaps.

VII SYNCHRONIZATION OF SPARK GAP DISCHARGES

After maki-- the radiation measurements described in the preceding section, attemp. ere made to measure the time difference between the avalanching in apparently synchronized spark gaps. Individual unit oscillators, similar to the one shown in Fig. 25, were operated in close proximity. When the spark discharges of neighboring oscillators were separated by a few inches or less, the ultraviolet flash from one discharge would trigger its neighbor and both oscillators would discharge in unison. The apparent synchronization could be destroyed by placing an opaque screen between neighboring oscillators.

The jitter-time between apparently synchronized oscillators was measured using a streak camera. The results of five measurements indicated an average jitter-time, or time displacement between avalanches in neighboring gaps, of 115 ± 2 nanoseconds (nsec). Since coherent radiation at 30 Mc from a ring transmitter would require that the spark gap discharges be synchronized to within 5-10 nsec, it is evident that the spark discharges must be synchronized with a precision greater than was achieved in these experiments.

We found that Godlove[4] and workers at Field Emission Corporation* have been able to synchronize spark gaps to within a few nanoseconds. These small jitter-times are achieved by pressurizing the gaps--the resulting smaller spark gaps having a shorter avalanche time--and by triggering the gaps with a flash of ultraviolet light. The ultraviolet flash is obtained from an auxiliary spark gap that is discharged at a very large overvoltage derived from a sharp pulse. The technique for

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[4] T. F. Godlove, "Nanosecond Triggering of Air Gaps with Intense Ultraviolet Light," Journal of Applied Physics Vol. 32, No. 8, p. 1589 (August 1961).

*Field Emission Corporation (private communication).

obtaining a short-rise-time, high-voltage trigger pulse, as described by Godlove, is shown in a schematic diagram in Fig. 26.

In order to incorporate the triggering technique in the ring transmitter, it was necessary to rebuild the spark gaps in the 24-Mc model. The original 67 spark gaps were replaced with pressurized, adjustable gaps. Each gap now is enclosed in an individual plastic cylinder that can be pressurized with nitrogen gap up to 90 lbs/square inch. In each cylinder there is also an auxiliary trigger gap. The trigger gaps are excited by a fast-rising overvoltage pulse, such pulse being derived from a modification of Godlove's circuit. A photograph of a pressurized unit is shown in Fig. 27.

After the ring was rebuilt, it was tested with only three of the 67 units operating. Of the three units chosen for testing, two units were at opposite sides of the ring and the third unit was at a position midway between the first two units. In a series of measurements we found that the average jitter-time--the difference in times of discharge for the three gaps--was about 300 nsec. A photograph of oscilloscope traces, showing the time difference between the trigger pulses, is shown in Fig. 28(a). This average jitter-time is worse than the 115 nsec jitter-time that we measured for two closely-spaced, unit oscillators.

In order to increase the overvoltage on the trigger gaps, and thus reduce avalanche time, we biased the trigger gaps with an additional 8 kv. Since the bias voltage was in series with the trigger pulse voltage, the overvoltage at the time of breakdown was greater. However the bias voltage, by itself, was insufficient to cause self-triggering of the trigger gaps. With this arrangement we succeeded in reducing the jitter-time to 10 or 15 nsec. A photograph of the oscilloscope trace for the biased trigger gaps is shown in Fig. 28(b). Since 5 nsec of jitter-time could derive from the finite propagation time of electromagnetic energy across the radius of the ring transmitter, it is possible that the three trigger gaps were synchronized to within 5 to 10 nsec. We were unable to modify all of the circuits to apply bias voltage to all 67 gaps before the end of this phase of the project. Additional testing of synchronization will be conducted as soon as bias voltage can be applied to all trigger circuits.

We believe that ultraviolet triggering of multiple spark gaps will prove to be a practical way of obtaining synchronous firing of gaps but that adjustment of circuitry and further experimentation time is required to prove out this technique.

VIII EXPERIMENTS WITH GAP PRESSURIZATION

A photograph of the test-bed 24-Mc transmitter, with 67 pressurized gaps installed, is shown in Fig. 29. In the previous section ultraviolet triggering, as a means of improving gap synchronization, was discussed. We mentioned in Section IV that power output from the original 24-Mc ring transmitter, with open-air spark gaps, fell some three orders of magnitude below expected theoretical levels. The radiation measurements (Section VI and observations made with a high-speed streak camera established gap avalanche time as sufficiently slow for charge redistribution to occur at very early times. Redistribution destroys the uniformity of the oscillations during the pulse. Further measurements of the ac resistance of a typical spark discharge (voltmeter-ammeter method) showed that dynamic resistance of the spark in air was 0.4 to 1.0 ohm. This result indicated that the total spark losses for 67 gaps (26 to 67 ohms) were greater than the desired radiation losses. The three-orders-of-magnitude power deficit was then believed to be due to lack of synchronism of gaps and high resistive losses. Another factor previously noted is the relatively high inductance of the long (1 cm) air spark, which means that the frequency of the ring is affected by electrode spacing.

As indicated in the previous section, ultraviolet triggering has not yet been sufficiently evaluated to ascertain its full effectiveness in synchronizing the gaps. However, the use of pressurized gaps alone has been found to bring a tremendous improvement to the operation of the 24-Mc ring transmitter.

The use of pressurized gaps (20 to 80 psi) permits a much smaller gap spacing (typically 0.025 inch) for a given charging voltage. The resultant spark is thicker and shorter. Since the same energy is concentrated in a smaller volume of air, the ion concentration is increased and the spark channel resistance greatly reduced. When the transmitted pulse from the ring was observed remotely, while the pressure and gap spacing were changed, it was found that the power output increased almost in direct proportion to gap pressure, charging voltage remaining constant. A means of reducing gap losses was thus confirmed.

The shorter spark channel length also reduces spark inductance to negligible values so the effect of gap adjustment on transmitter frequency is less important.

A shorter gap spacing also speeds the process of spark channel formation so that gap asynchronism problems are reduced. When a single gap in the ring spark transmitter fires, the other gaps are immediately overvoltaged, and this greatly reduces the avalanche time of the remaining gaps.[5] Thus the ring has an inherent self-avalanching feature which tends to induce gap synchronism. It is evidently this cascading effect which resulted in significant coherent energy being radiated by the 470-Mc ring transmitter, even when no attempts were made to trigger or pressurize the gaps.

Our findings in recent weeks indicate that pre[illegible] of gaps without ultraviolet triggering results in the recovery of most of the lost power output. Figure 30 shows clutter echoes obtained from Black Mountain and the coastal foothills behind Stanford University from the 24-Mc ring transmitter, using pressurized gaps operated at about 60 psi. These echoes are some two orders of magnitude larger than echoes from the same target previously obtained with unpressurized gaps and higher charging voltage.

Figure 31 shows the pulse waveform of the transmitted pulse observed directly on the deflection plates of a high-speed oscilloscope connected to a 50-ohm antenna located 300 meters from the transmitter ring. The pulse is seen as fairly monochromatic, smooth, and free from abrupt discontinuities. The rising front edge of the pulse envelope indicates that the spark channel resistance decreases with time as the channel

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[5] B. J. Elliott, "On the Generation of Intense Fast-Rising Magnetic Field Pulses," M.L. Report 1095, Contract DA 36-039 AMC-00041(E), DA Project No. 3A99-21-001 USAERDL, Stanford University, Stanford, California (October 1963).

undergoes heating and expansion. The pulse length is close to the 1-microsecond calculated value, which indicates that the operating Q is close to the expected value.

In the near field of the ring transmitter (up to about 100 feet) small neon bulbs and fluorescent lamps can be lighted, and transistors in electronic equipment are occasionally destroyed. Spurious responses are excited in receivers and other equipment; however, this is to be expected for a device radiating such high peak powers. The field 300 meters away is uniform and there is an absence of spurious and parasitic frequencies. The electrical noise from the gaps and near-field ir[illegible] radiations probably can be reduced by electrostatic shielding of the ring.

The principle lobe of the 24-Mc ring transmitter is directed upwards at a moderately steep angle due to the conducting ground just below the ring. This pattern of radiation makes it difficult to measure the peak power at a ground location, since the receiver will be picking up energy well below the maximum of the main lobe. Measurements 300 meters from the transmitter ring indicated 140 kw peak power at a ring operating voltage of 18 kv. Peak power was found to be directly proportional to charging voltage, so that increasing the voltage to the design level of 50 kv should result in a measured power of about 370 kw. Taking the antenna pattern into consideration we believe the actual radiated power was probably much higher.

Further measurements of the pattern and power output are now underway. We tentatively conclude that gap pressurization so significantly improves the operation of the ring transmitter that it can be considered a practical and workable device. Ultraviolet triggering may be a means of effecting a still further improvement in efficiency, and, of course, still higher pressures also should be tried.

IX SOME APPLICATIONS OF THE RING SPARK TRANSMITTER

The ring spark transmitter is a combination transmitter and antenna. Basically, its radiation pattern is that of a magnetic dipole (Fig. 11), although there is a wide latitude of control over the lobes and beamwidth by varying the ratio of diameter to wavelength. The unit can be placed remotely from its power supply, connected by a suitable high-voltage cable such as RG 8/U or RG 17/U coax, or commerical X-ray cables. If the gaps are not permanently pressurized, a small gas hose line is also required. Ultraviolet triggering circuitry would also necessitate running a small trigger line from pulse generator to ring.

The ring transmitter is immediately adaptable as a feed assembly for a parabolic antenna (Fig. 32). Parasitic elements behind or in front of the ring can be used to obtain correct illumination of the dish. This is frequently done with electric dipole antennas which are used as dish feeds, and the validity of this method has been established with the ring transmitter (Fig. 23).

An active array of ring antennas can be arranged along the ground as shown in Fig. 33 in order to obtain a steerable-beam antenna. In this scheme very high powers are obtained, but triggering of each ring would be necessary. To steer the beam, the triggering of one ring with respect to its neighbors would have to be controlled to within a small fraction of a wavelength; however, this now appears practical with present techniques.

The possibility of using the Landecker methods at VLF should not be overlooked. Figure 34 shows a possible VLF loop antenna supported from the ground on telephone poles. Suppose for sake of illustration that such a loop operates at 20 kc with 50 capacitors, each 8 microfarads, charged to 100 kv. The expected power level from such a transmitter would be of the order of 2000 Mw and the pulse length 1 msec. Such a design would not be expensive to build and test.

X CONCLUSIONS AND RECOMMENDATIONS

It is concluded that the ring spark transmitter proposed b Landecker, along lines suggested by Marconi, is a practical dev the generation of very high peak power in the high-frequency ra We believe that power levels of megawatts or higher are obtaina that powers of tens, hundreds, or thousands of megawatts may be

We conclude that CW or long pulse operation of the Landeck mitter, which depends on the dovclopment of a high-speed, high- plasma switch tube, cannot be achieved at this time.

We believe that practical ring spark transmitters can be bu operate to frequencies as high as a few hundred megacycles at pe of the order of megawatts or tens of megawatts.

Gap pressurization and/or triggering is required to reduce resistive losses and to reduce gap firing times, if power levels approach design expectations.

The ring transmitter methods are adaptable to VLF, where ve powers and long pulses should be achievable.

The ring transmitter can be combined with parasitic element produce various antenna patterns. The device can be used as the element for a parabolic dish antenna, or as in element in an act array.

The transmitted signal is fairly coherent, produces well-de clean radar returns, and is reasonably free from parasitics and radiations.

We recommend continued research along the following lines:

(1) Gap triggering and gap synchronism problems; pulse-to-pulse coherence.

(2) Experiments at VLF and UHF, study design and testing of devices to operate at these frequency extremes.

(3) Experiments with active arrays.

(4) Study of effects of pressurizing the spark gaps.

(5) Engineering improvements: packing and design of rugged transmitters for practical applications.

(6) Study of the influence of parasitic elements and secondary circuitry.

(7) Improve measurements of pulse power levels and efficiencies.

(8) Study modulation schemes, frequency stability, and tuning.

(9) Study pulse-stretching and shaping techniques.

(10) Measure near- and far-field spectra and radiation patterns from ring transmitters.

We encourage and recommend further research on these new transmitting devices which now appear to have promise when very high peak pulse powers are required at frequencies from VLF to UHF.

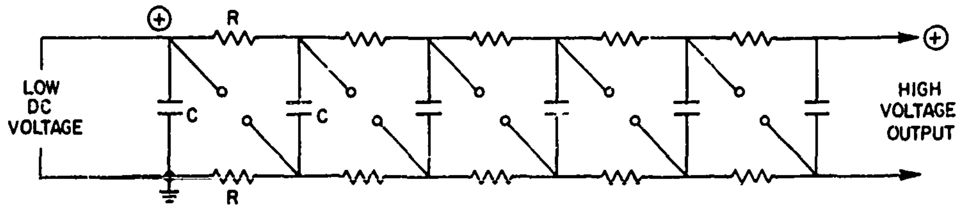

FIG. 1 MARX IMPULSE GENERATOR, SCHEMATIC DIAGRAM

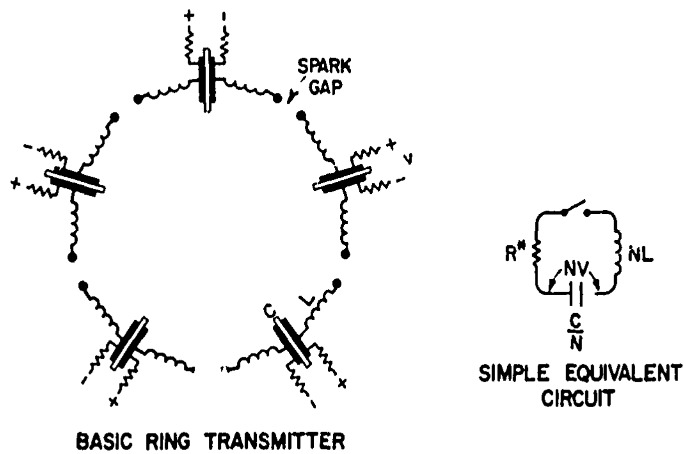

FIG. 2 ELEMENTARY LANDECKER RING SPARK TRANSMITTER, SCHEMATIC DIAGRAM

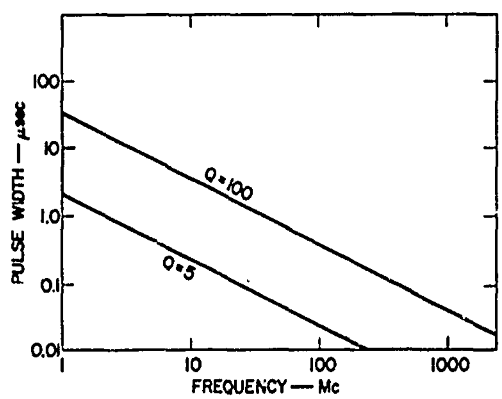

FIG. 3 TYPICAL PULSE WIDTH vs. FREQUENCY

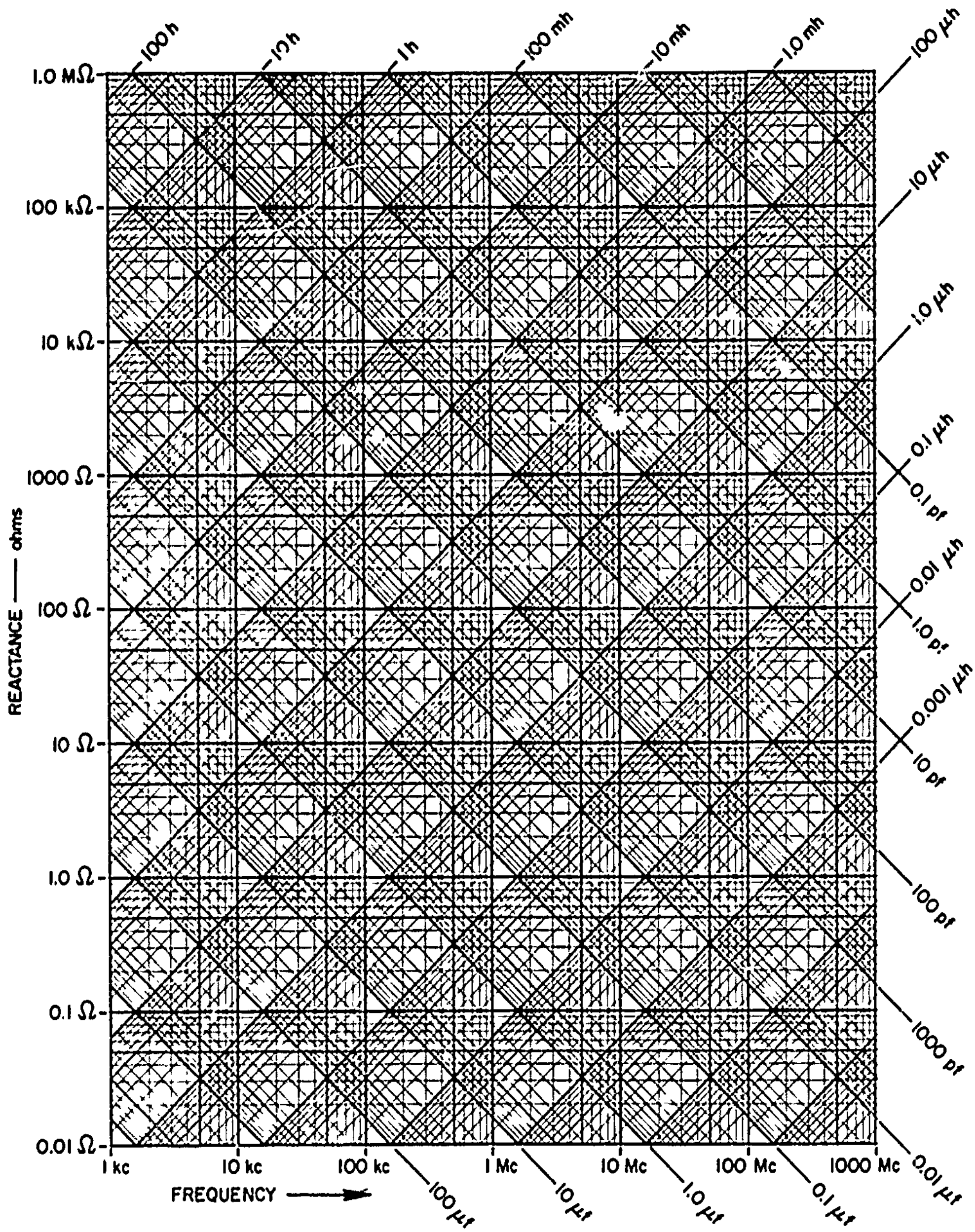

FIG. 4 REACTANCE CHART FOR RING TRANSMITTERS

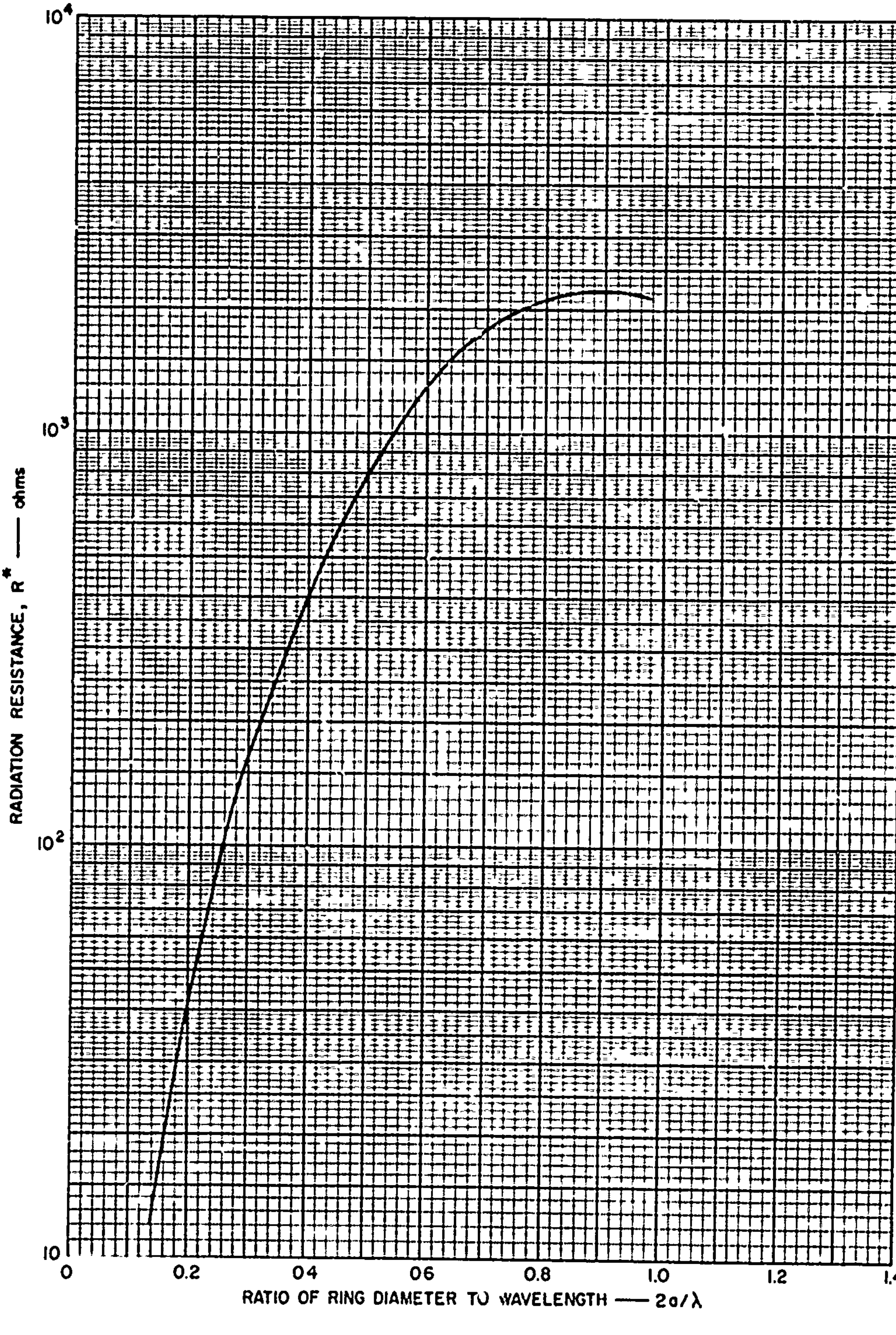

FIG. 5 RADIATION RESISTANCE OF CIRCULAR LOOP ANTENNAS

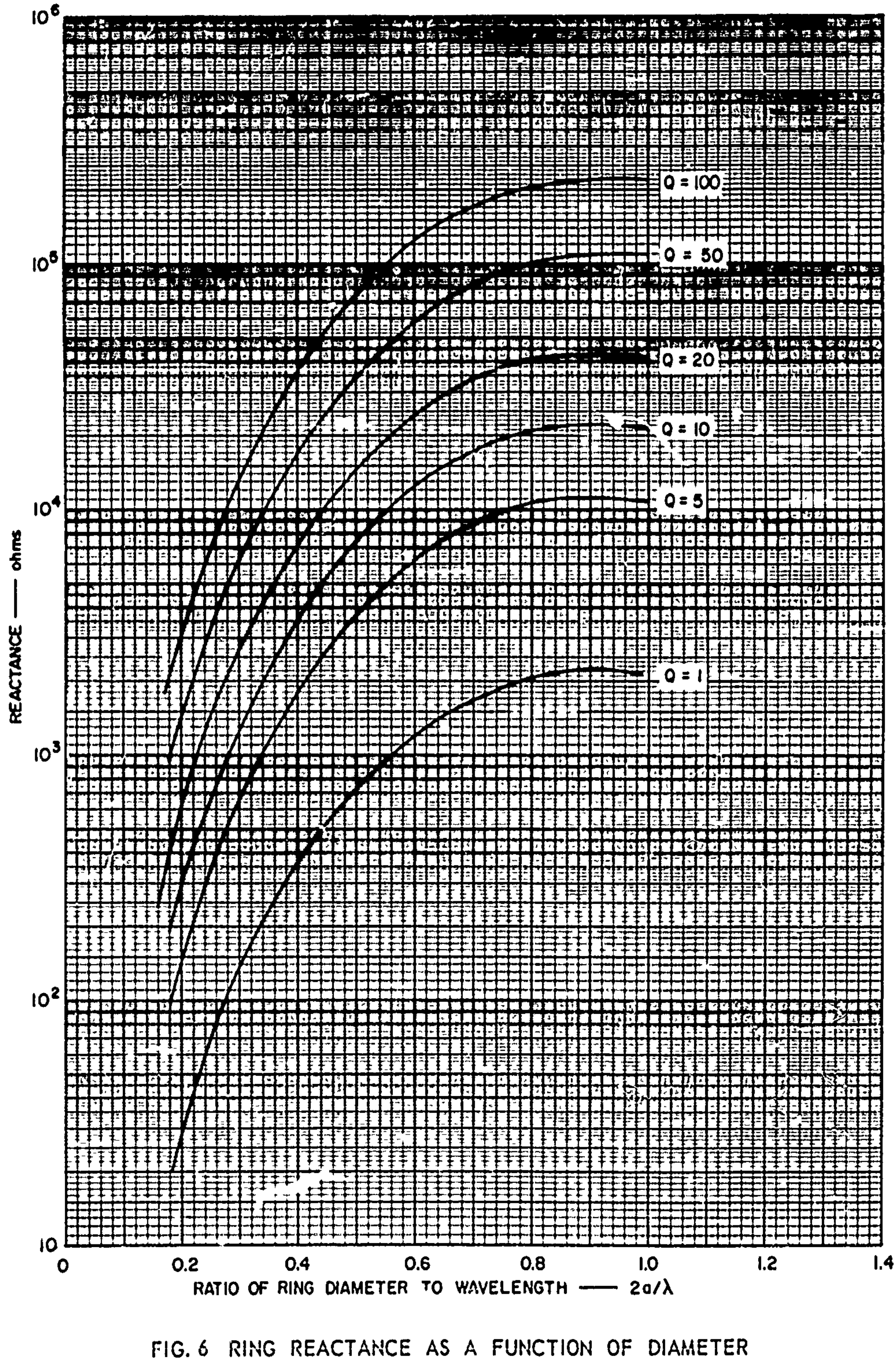

FIG. 6 RING REACTANCE AS A FUNCTION OF DIAMETER

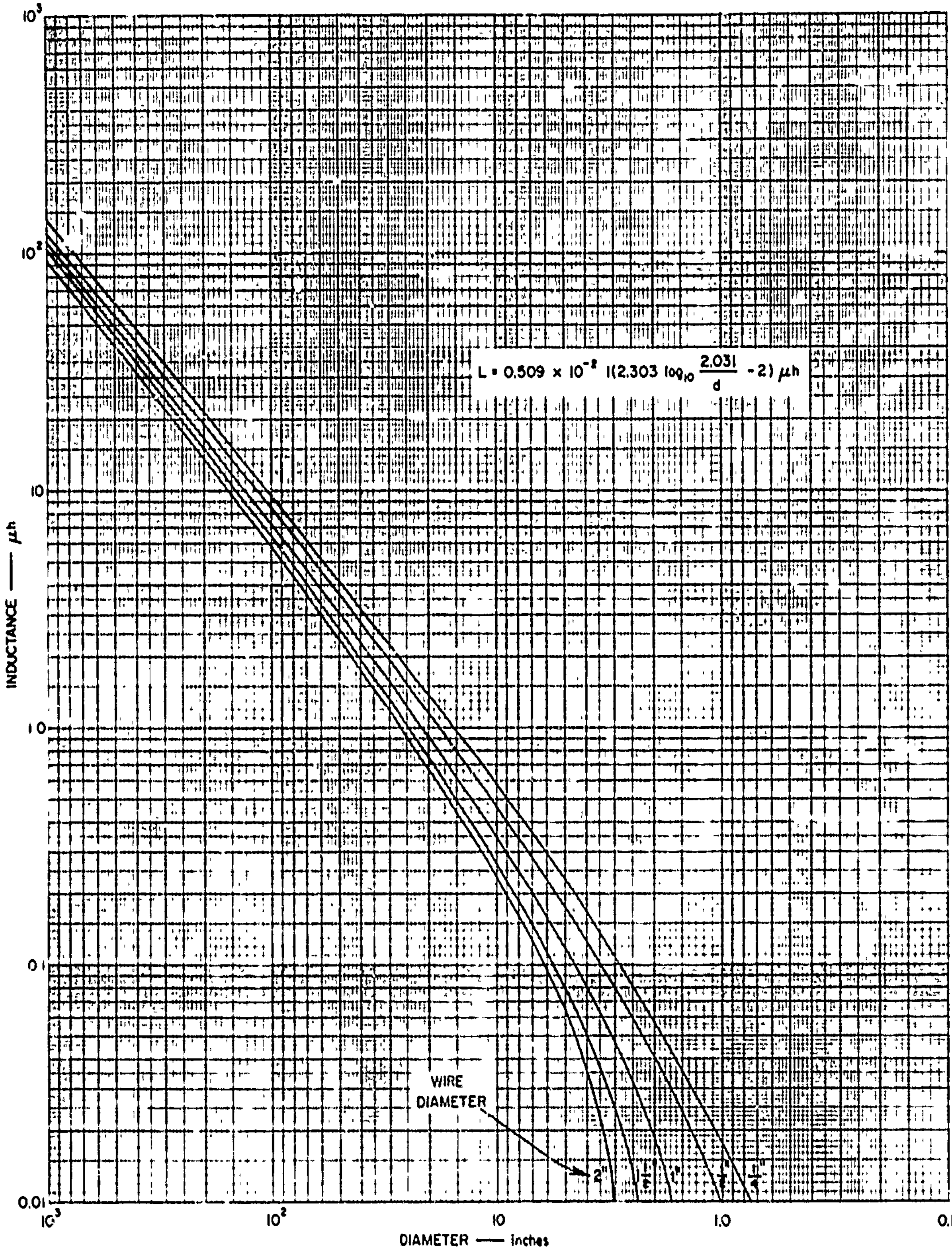

FIG. 7 INDUCTANCE OF CIRCULAR LOOPS vs. DIAMETER

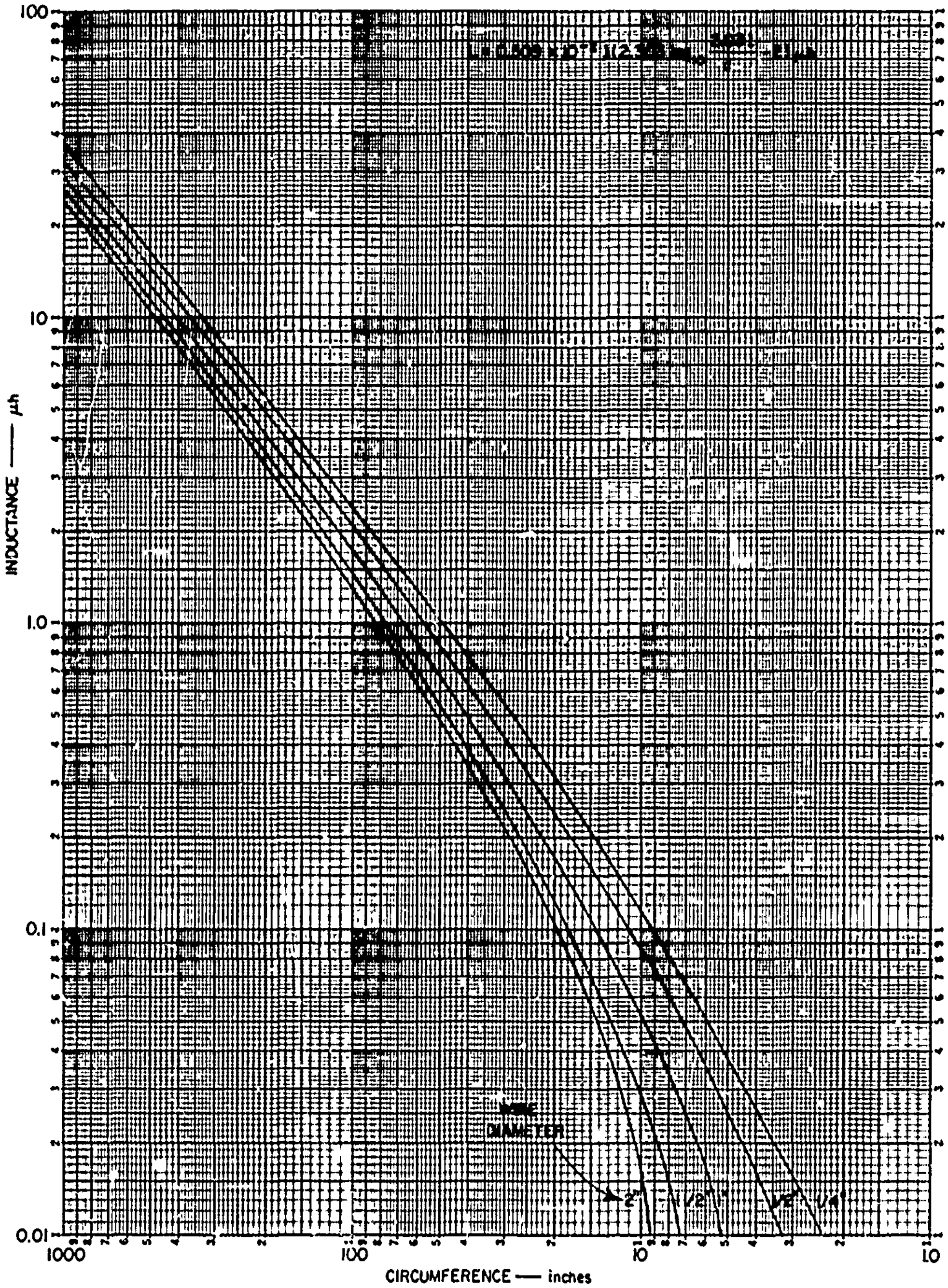

FIG. 8 INDUCTANCE OF CIRCULAR LOOPS vs. CIRCUMFERENCE

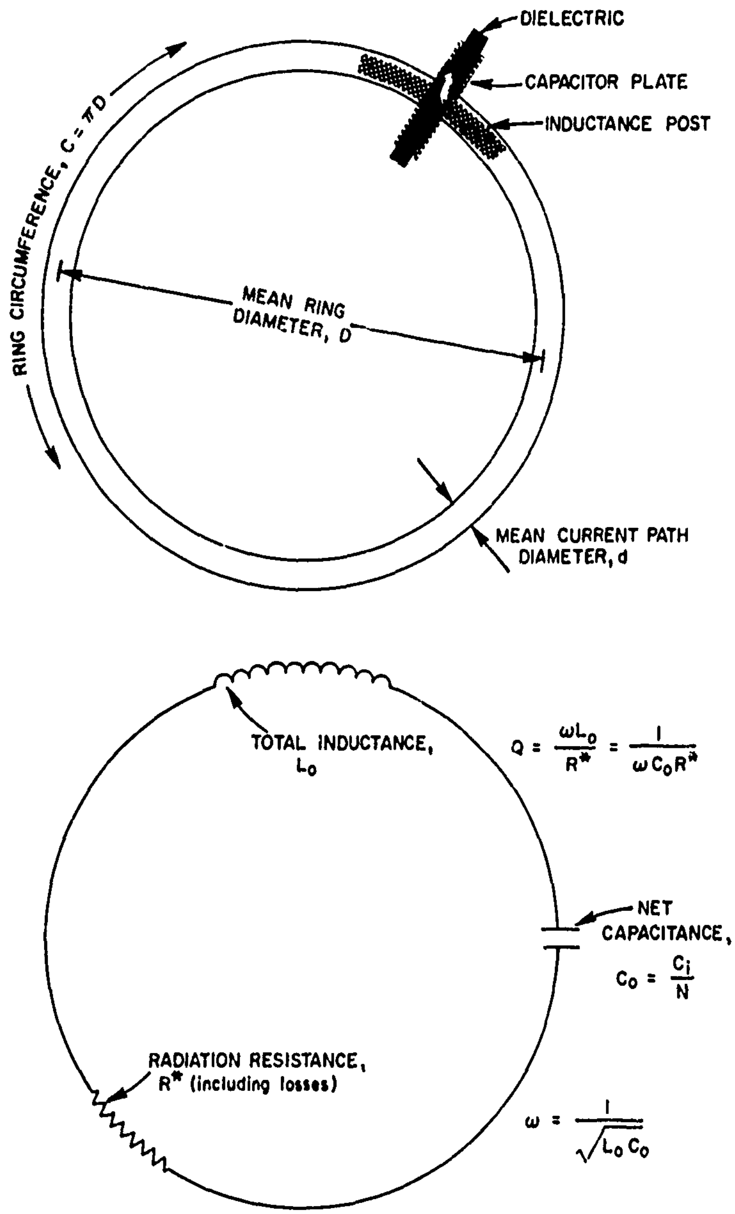

FIG. 9 GEOMETRY AND EQUIVALENT CIRCUIT OF RING TRANSMITTER

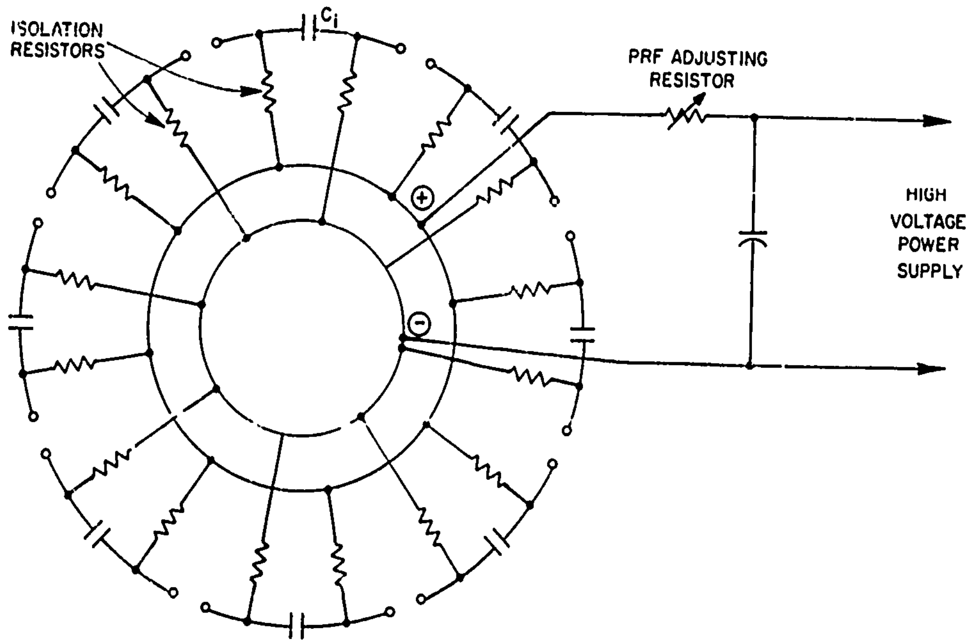

FIG. 10 DC CHARGING CIRCUITRY

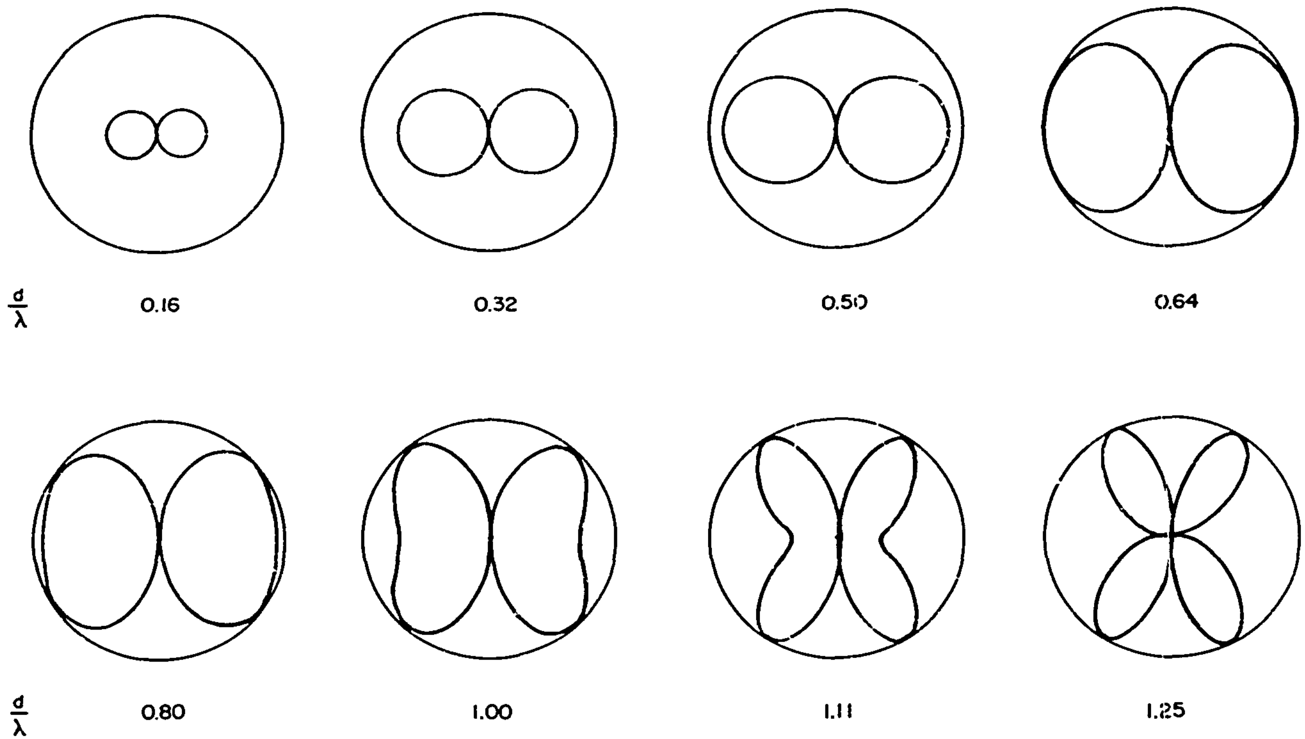

FIG. 11 RING TRANSMITTER RADIATION PATTERNS

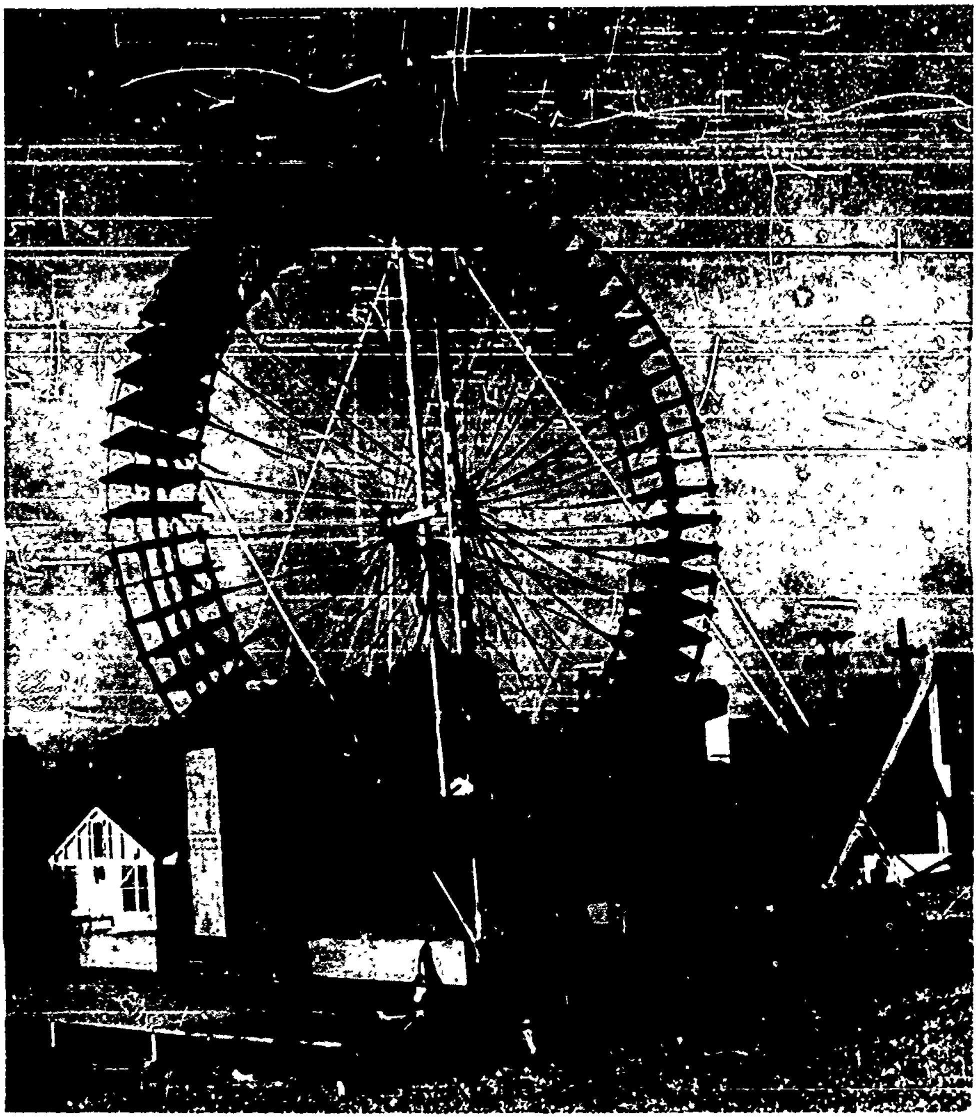

FIG. 12 24-Mc TRANSMITTER

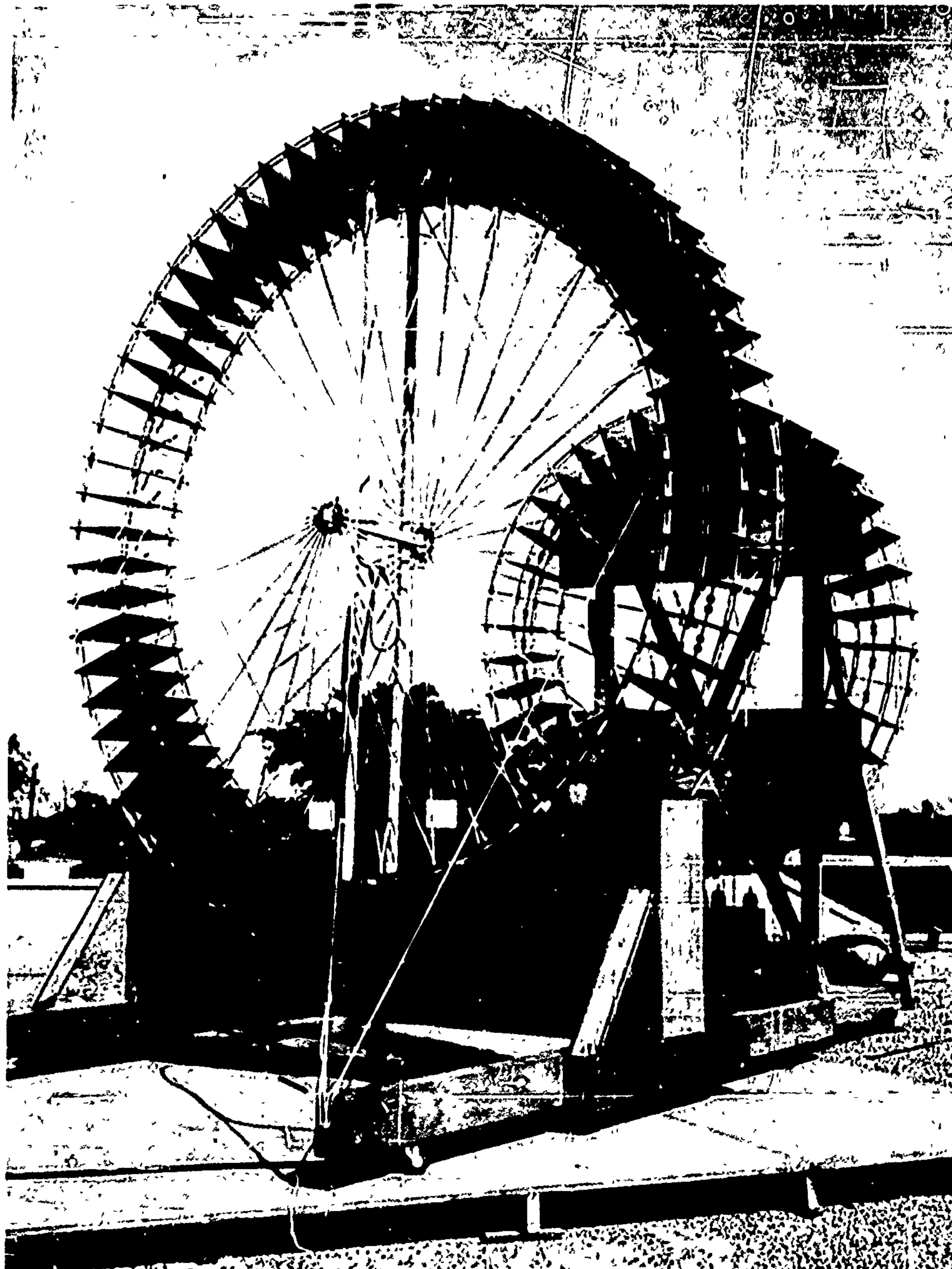

FIG. 13 24-Mc TRANSMITTER WITH SECONDARY RING

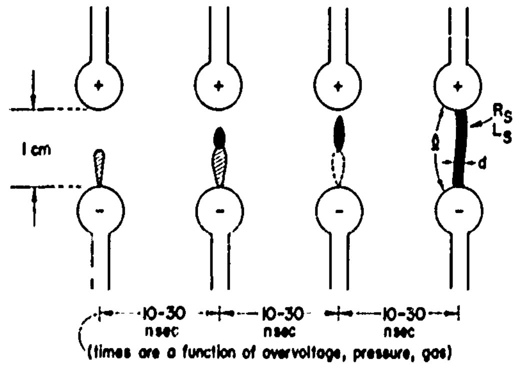

FIG. 14 BREAKDOWN OF A SPARK GAP

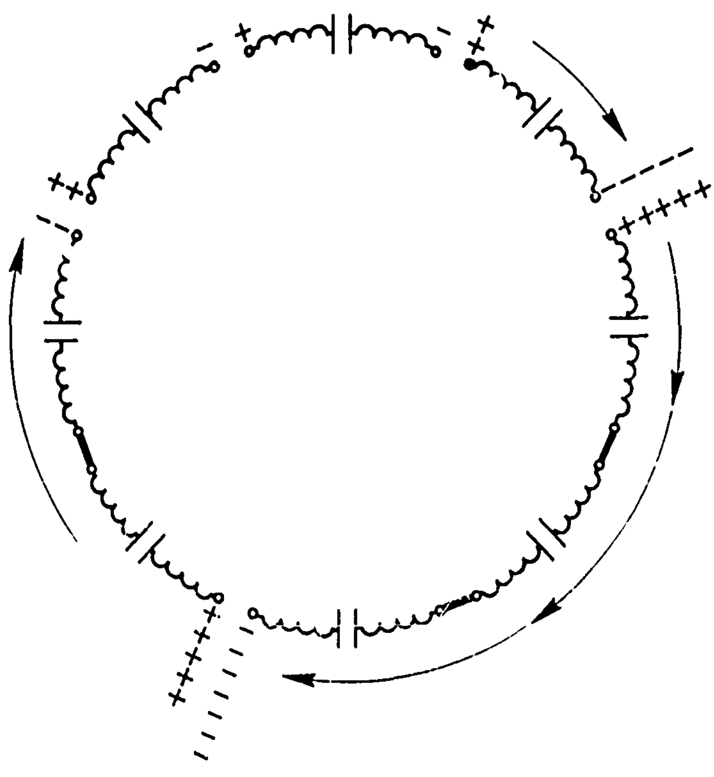

FIG. 15 CHARGE REDISTRIBUTION FROM GAP ASYNCHRONISM

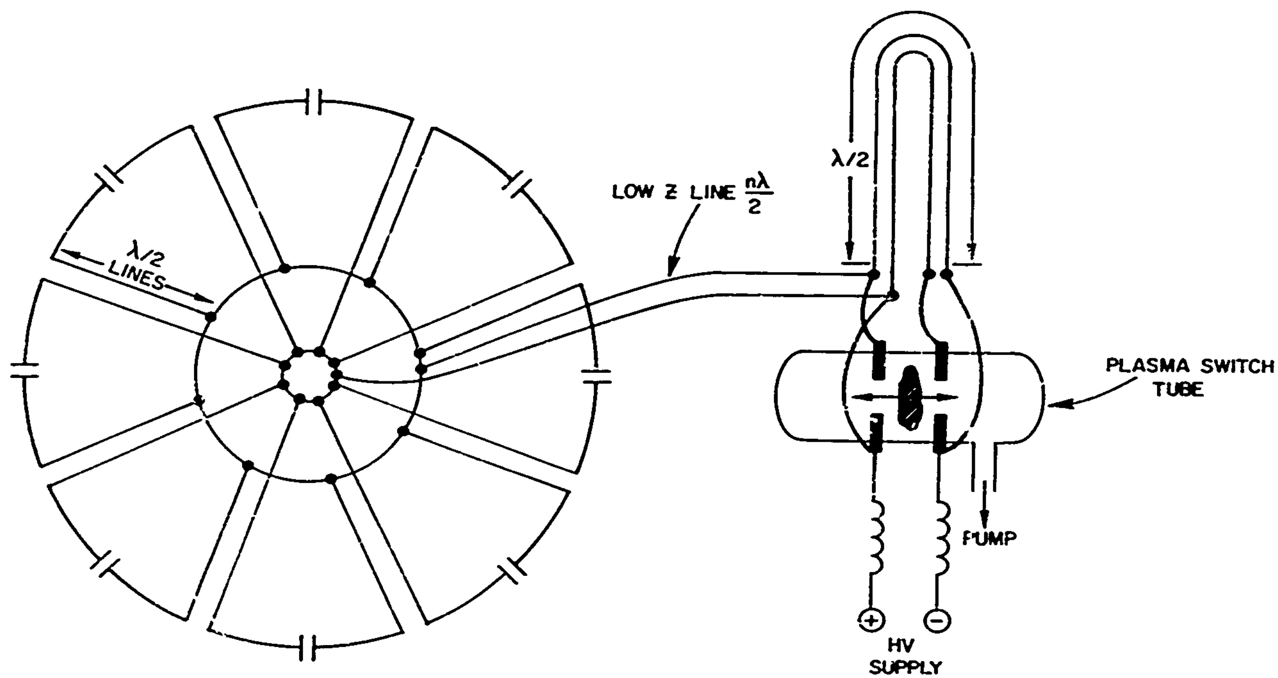

FIG. 16 RING TRANSMITTER WITH PLASMA SWITCH TUBE

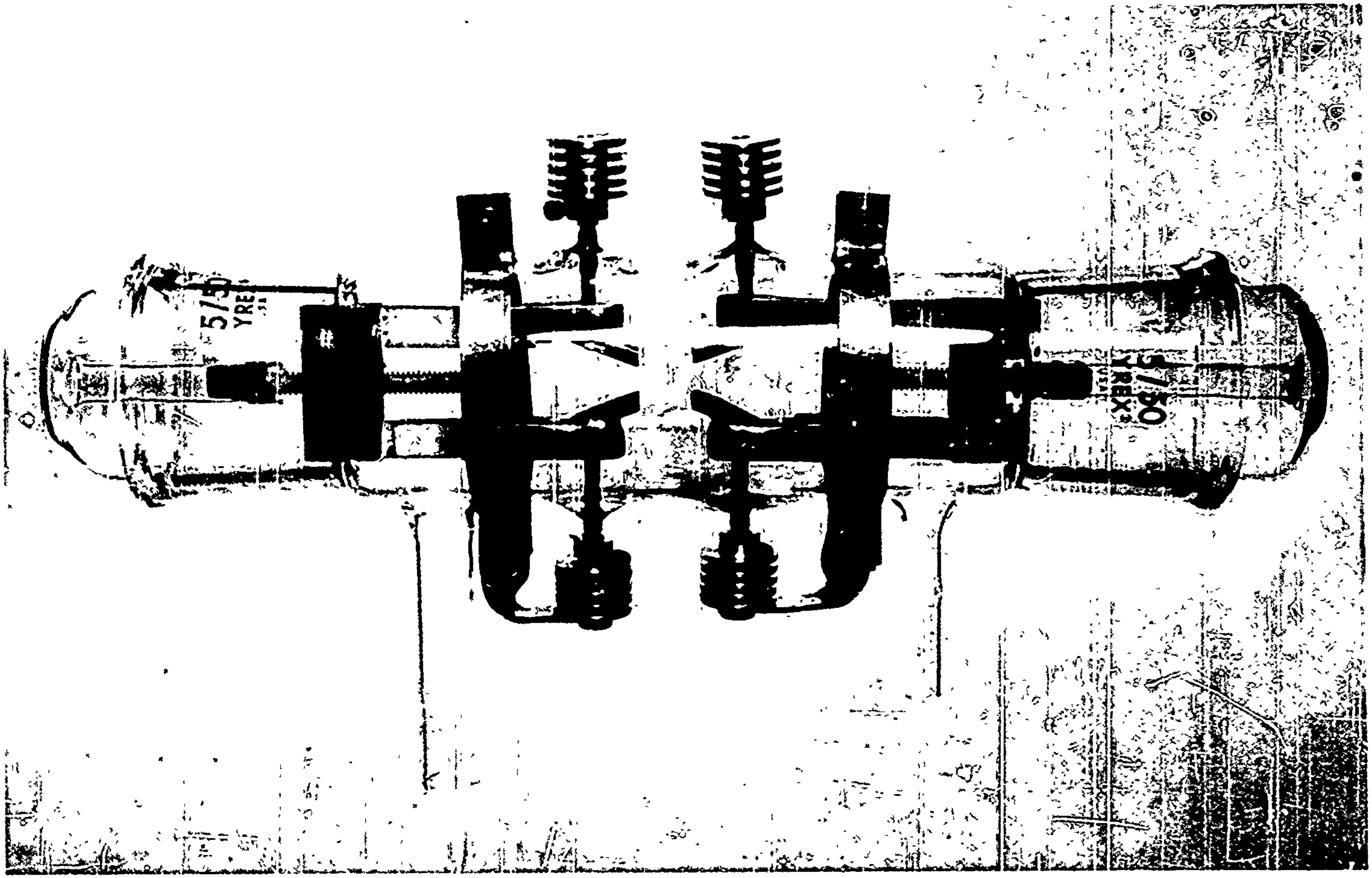

FIG. 17 PLASMA SWITCH TUBE WITH ADJUSTABLE ELECTRODES

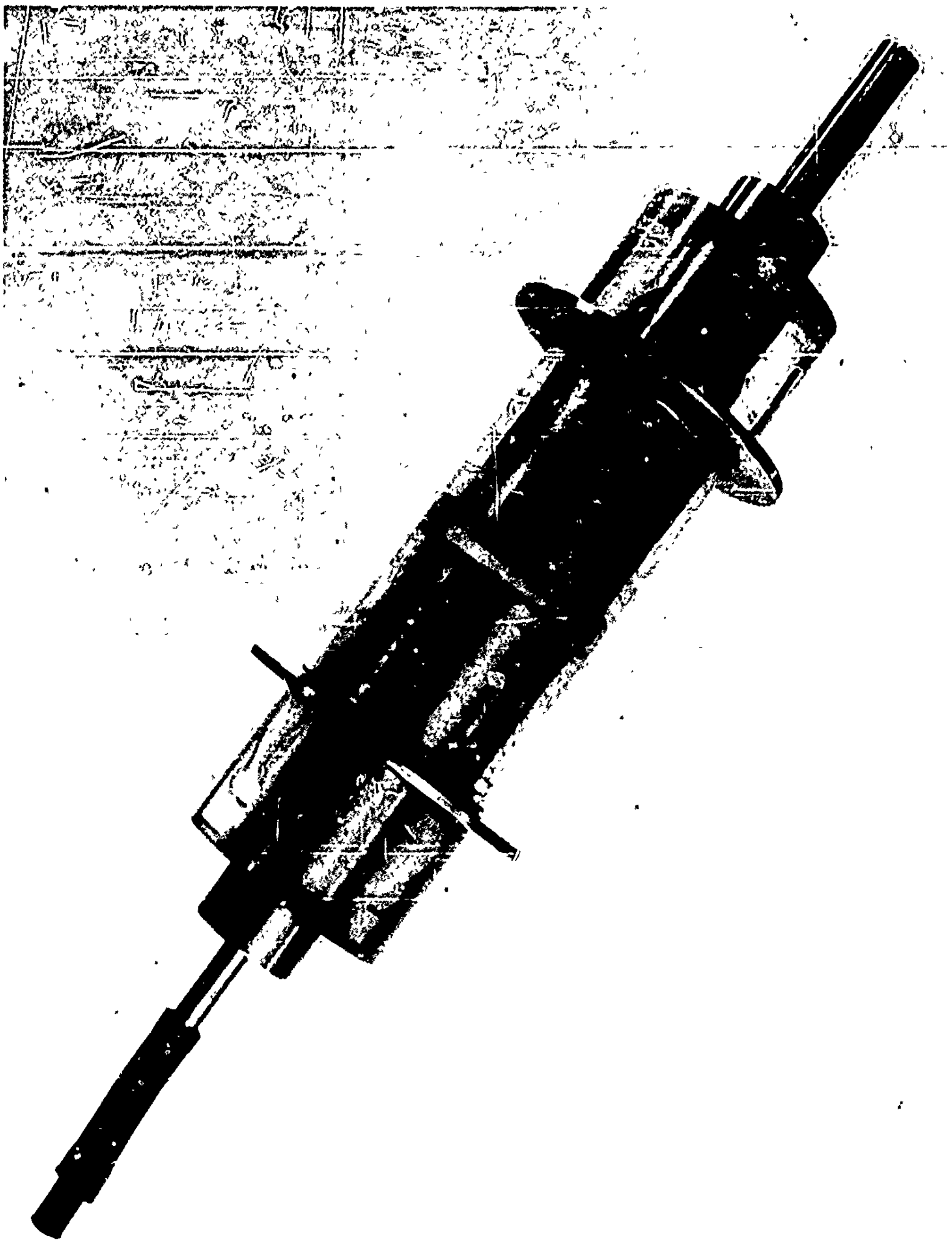

FIG. 18 SWITCH TUBE WITH CYLINDRICAL GEOMETRY

FIG. 19 ONE-METER SHOCK TUBE

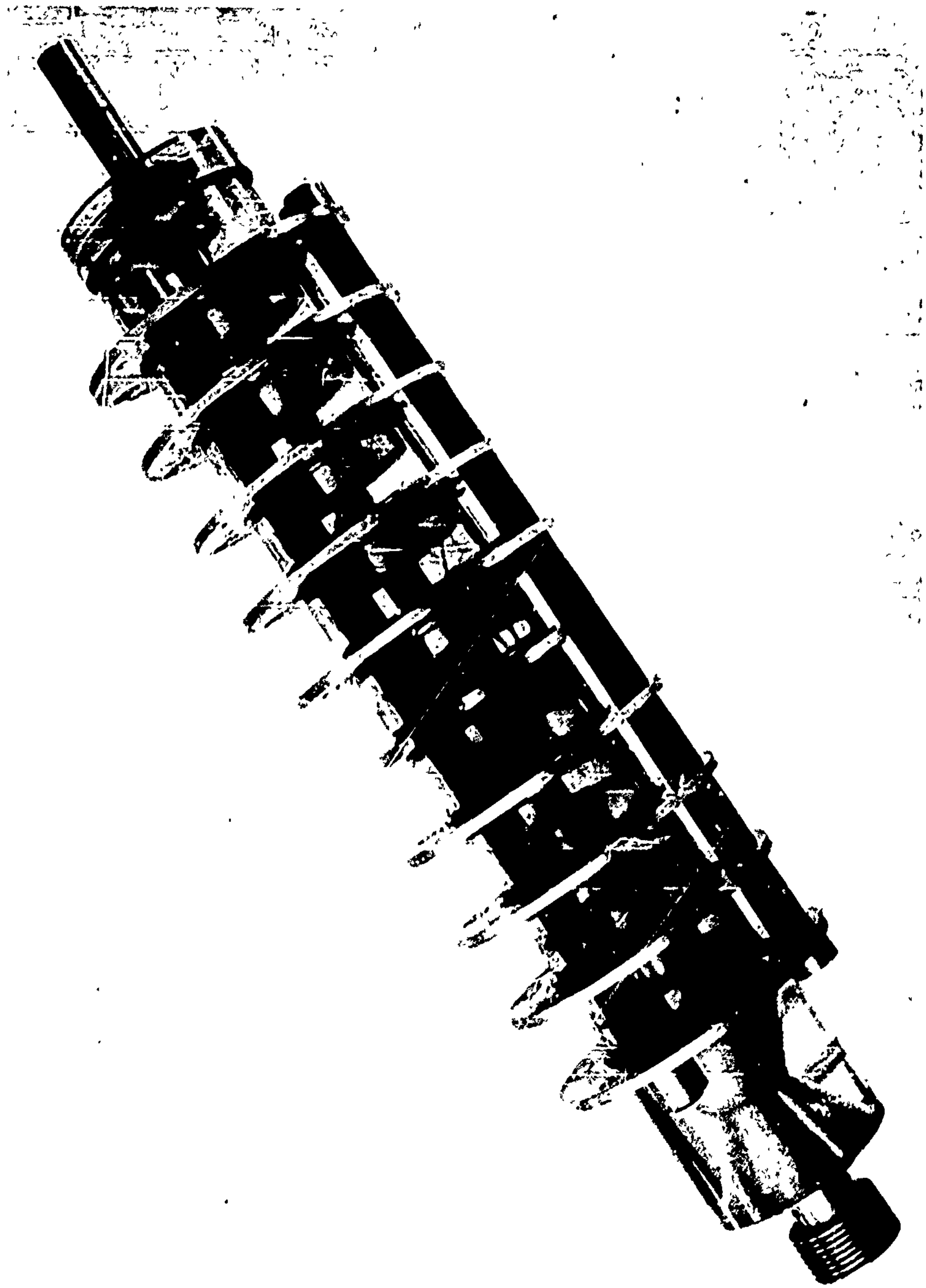

FIG. 20 CYLINDRICAL-GEOMETRY SWITCH TUBE WITH MULTIPLE ELECTRODES

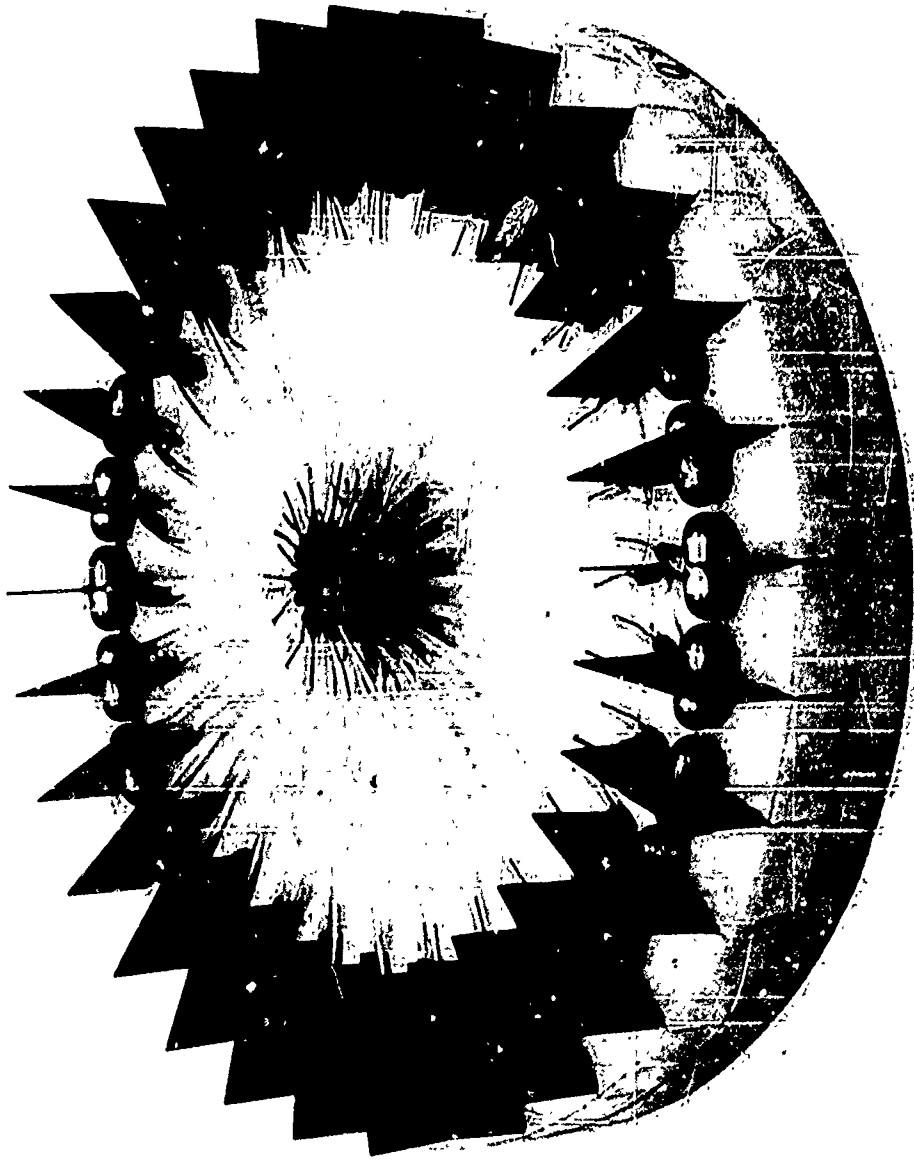

FIG. 21 SMALL UHF RING TRANSMITTER

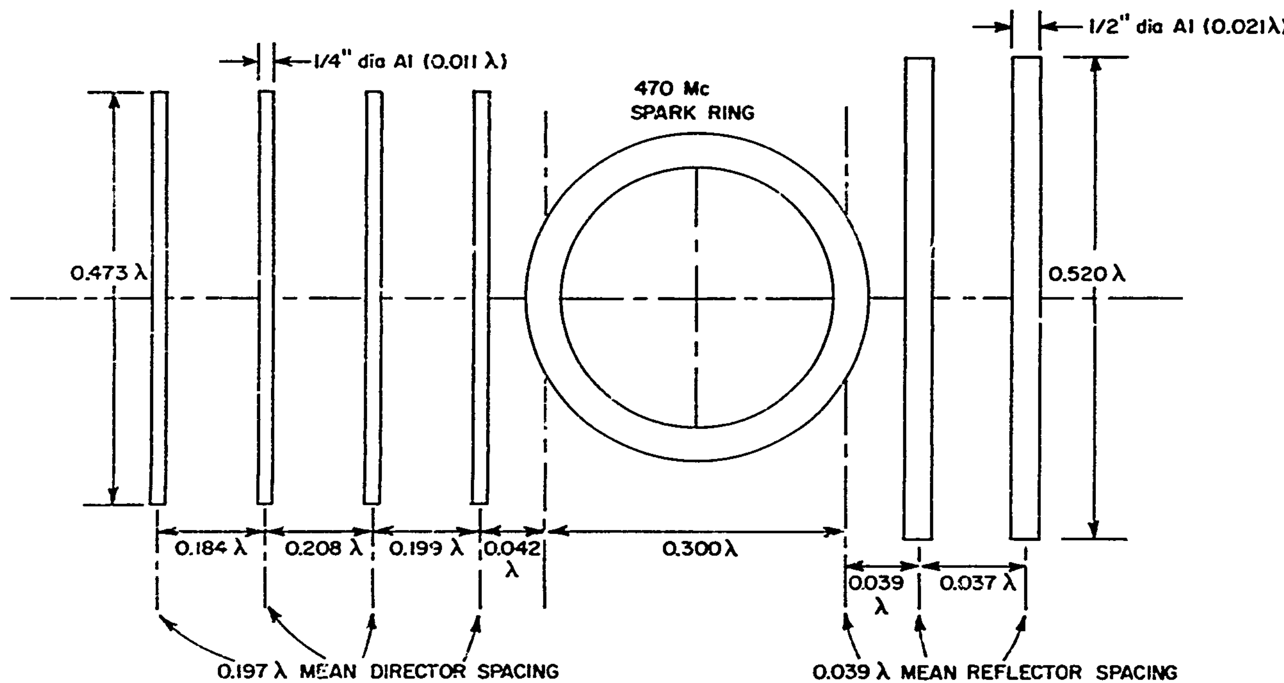

FIG. 22 UHF RING WITH PARASITIC ELEMENTS

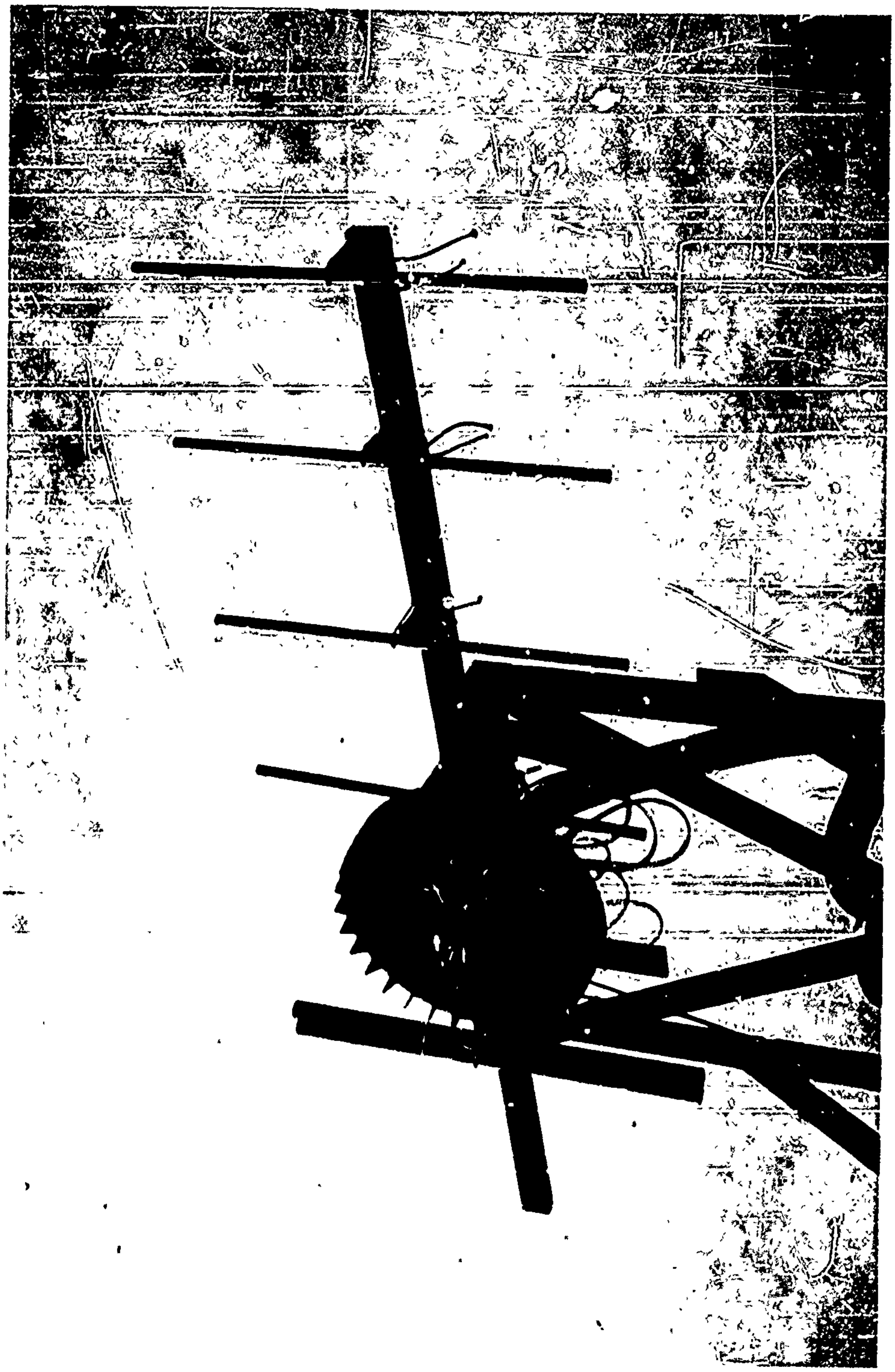

FIG. 23 UHF RING DURING PATTERN MEASUREMENTS

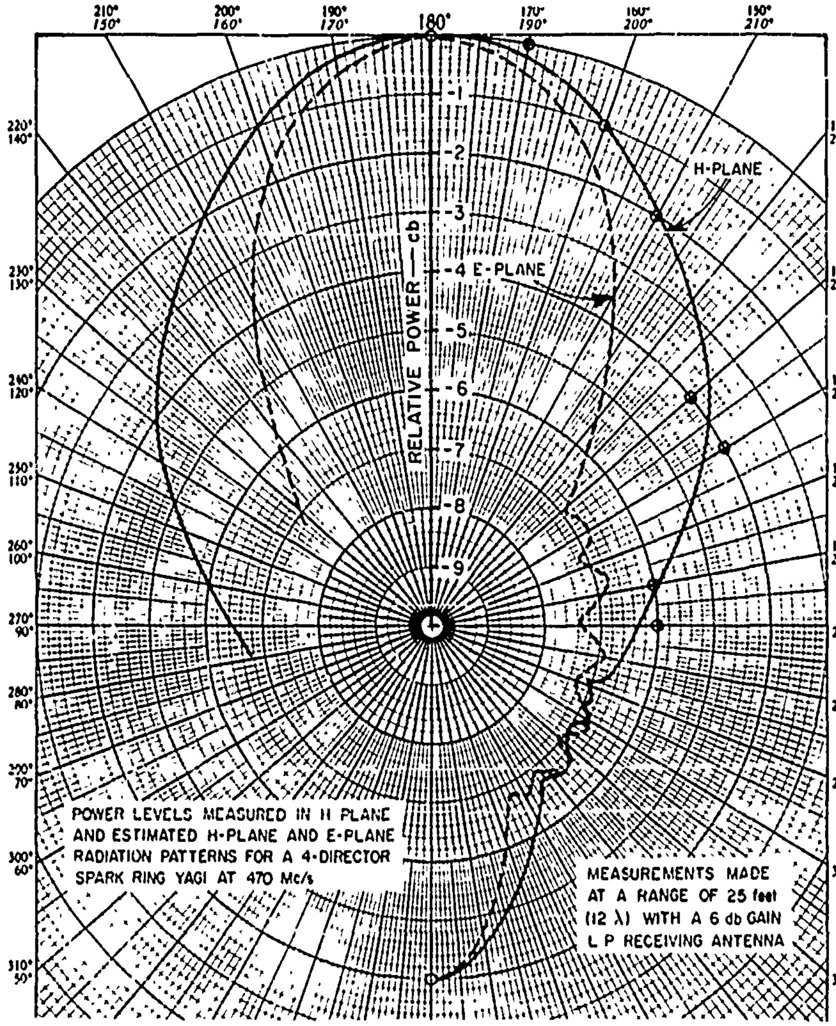

FIG. 24 ANTENNA PATTERN OF TRANSMITTER ARRAY

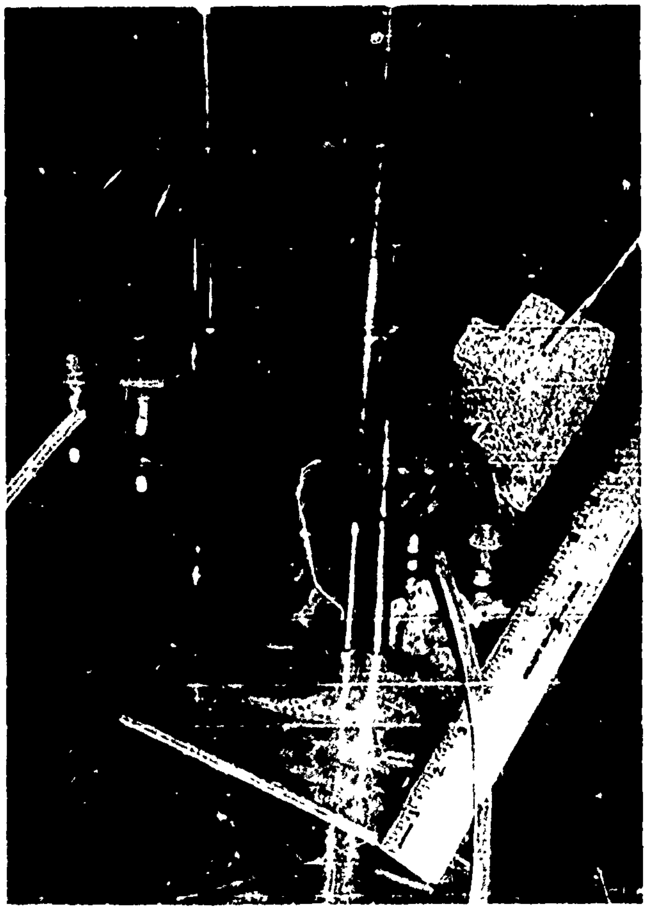

FIG. 25 UNIT OSCILLATORS FOR SYNCHRONIZATION EXPERIMENTS

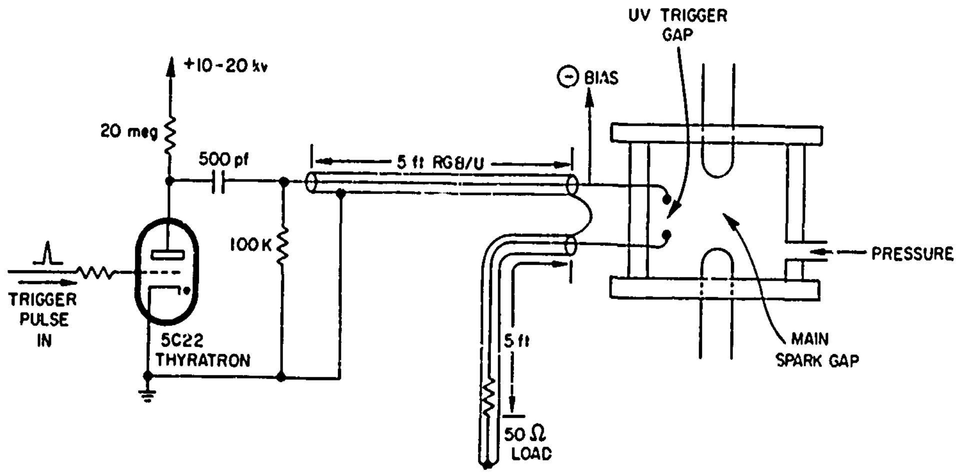

FIG. 26 ULTRAVIOLET GAP TRIGGER CIRCUIT

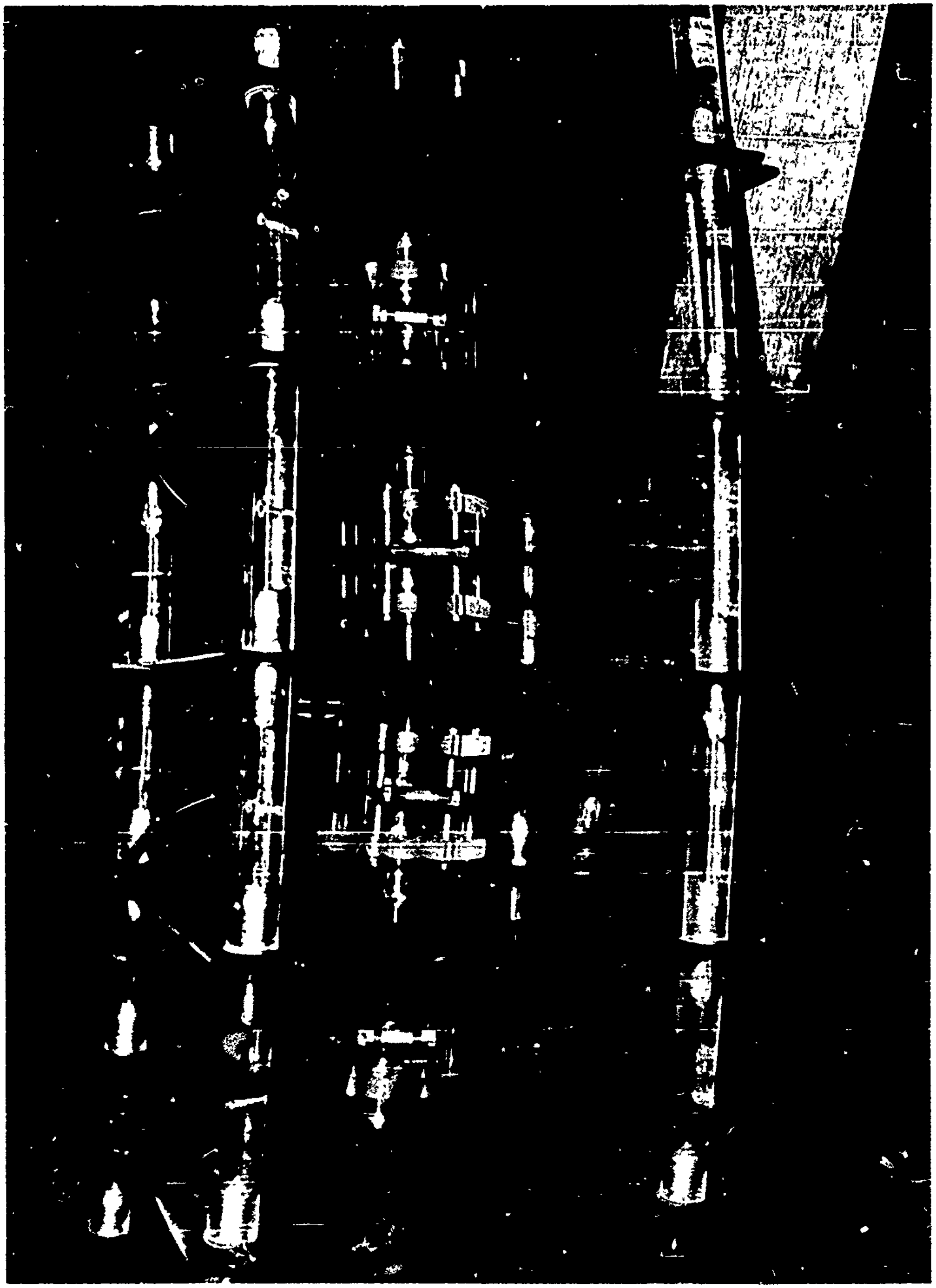

FIG. 27 PRESSURIZED SPARK GAP UNIT

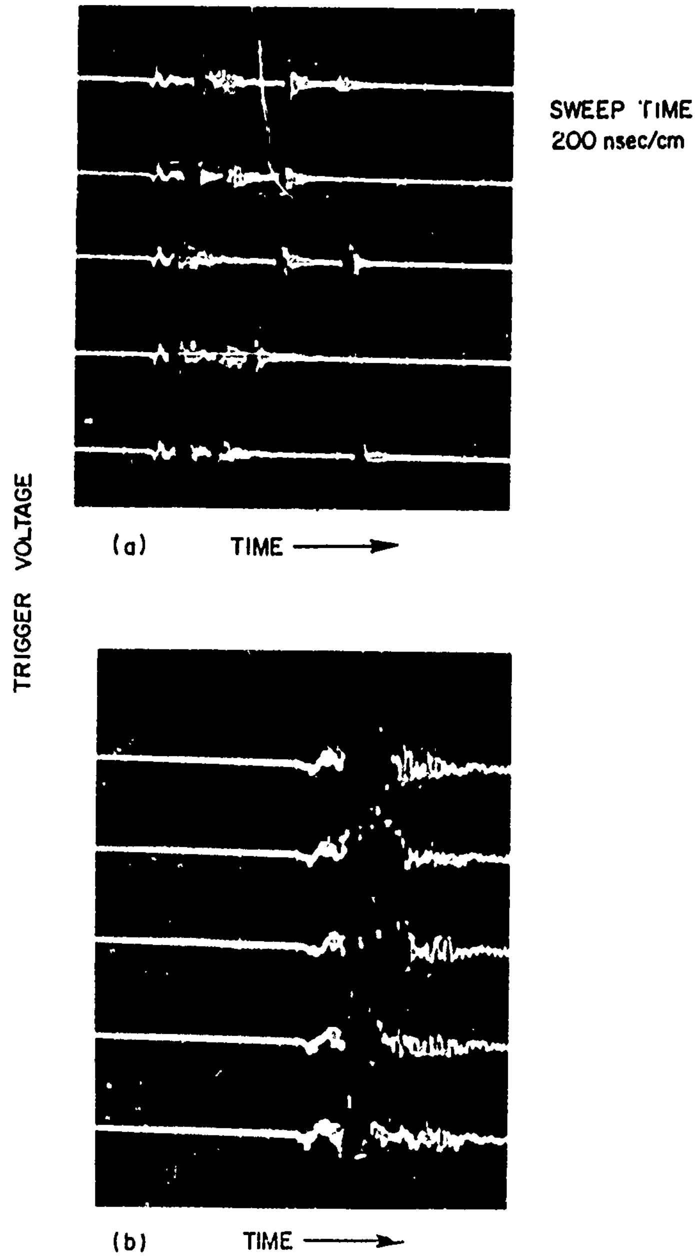

FIG. 28 TRIGGER GAP JITTERING
(a) Gaps not synchronized
(b) Gaps synchronized

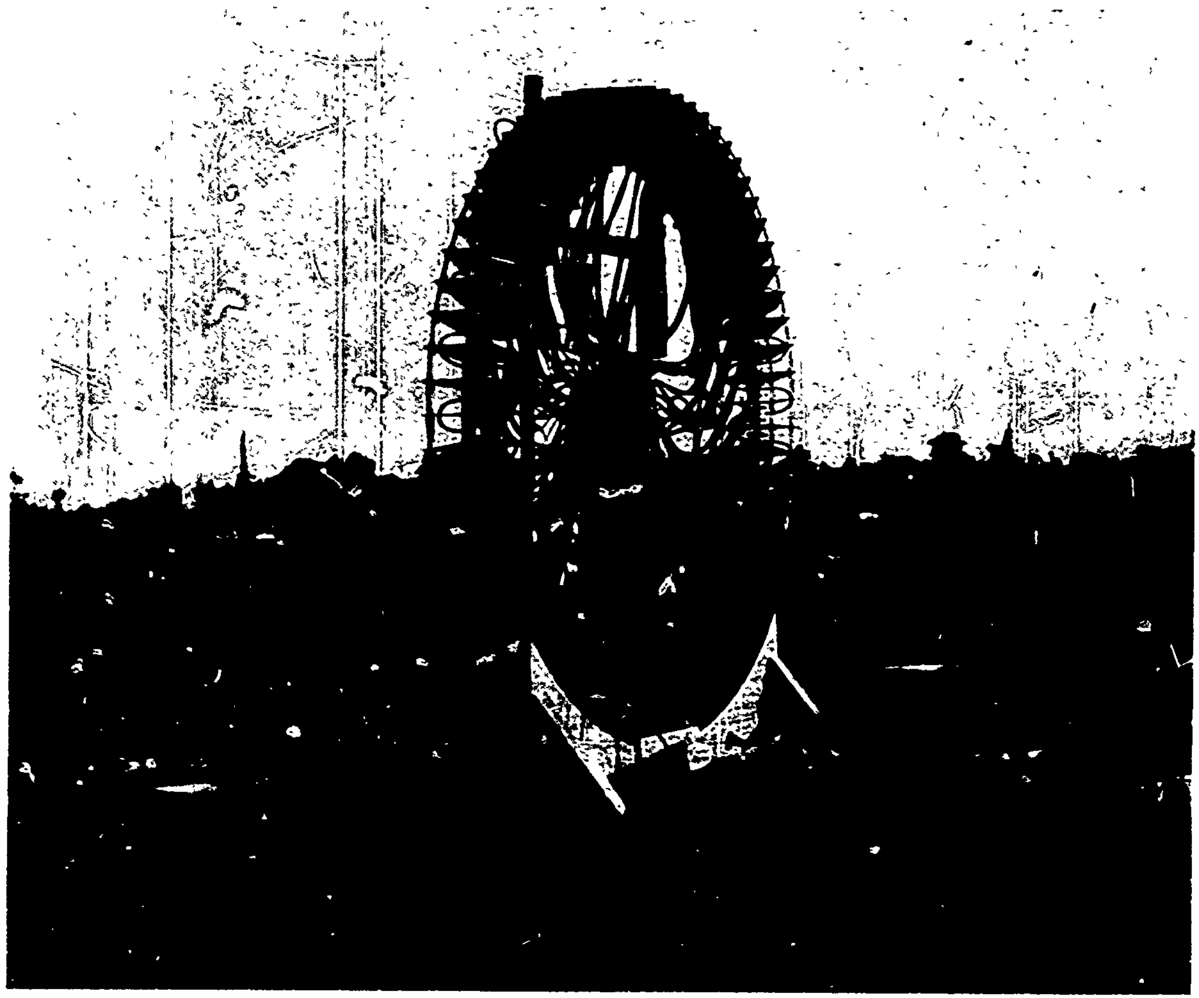

FIG. 29 24–Mc RING TRANSMITTER WITH PRESSURIZED GAPS

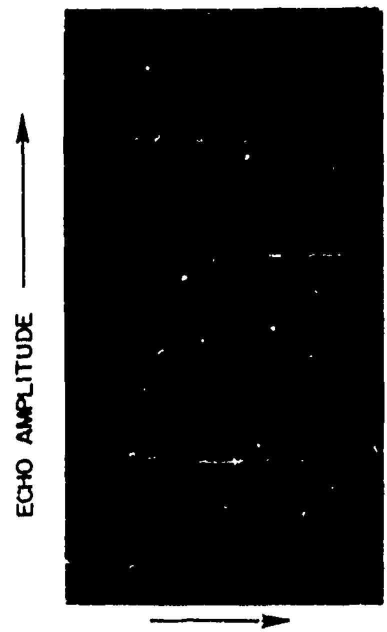

FIG. 30 A-SCOPE PRESENTATION OF CLUTTER ECHOES FROM 24-Mc TRANSMITTER

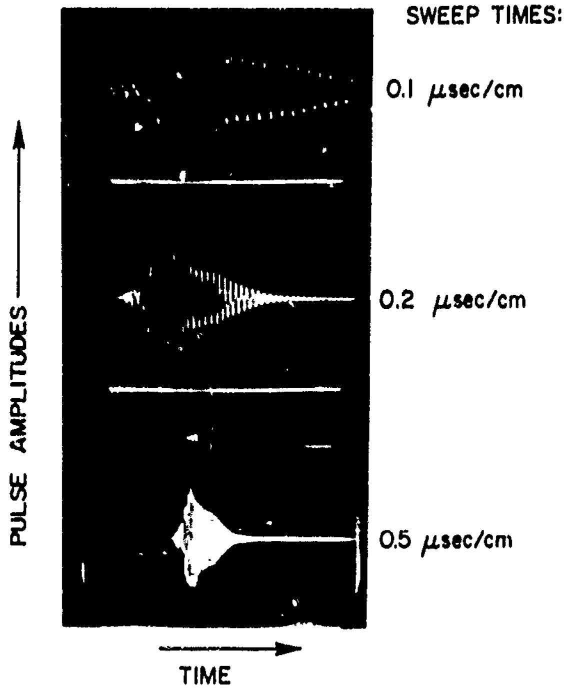

FIG. 31 PULSE WAVEFORM FROM 24-Mc TRANSMITTER

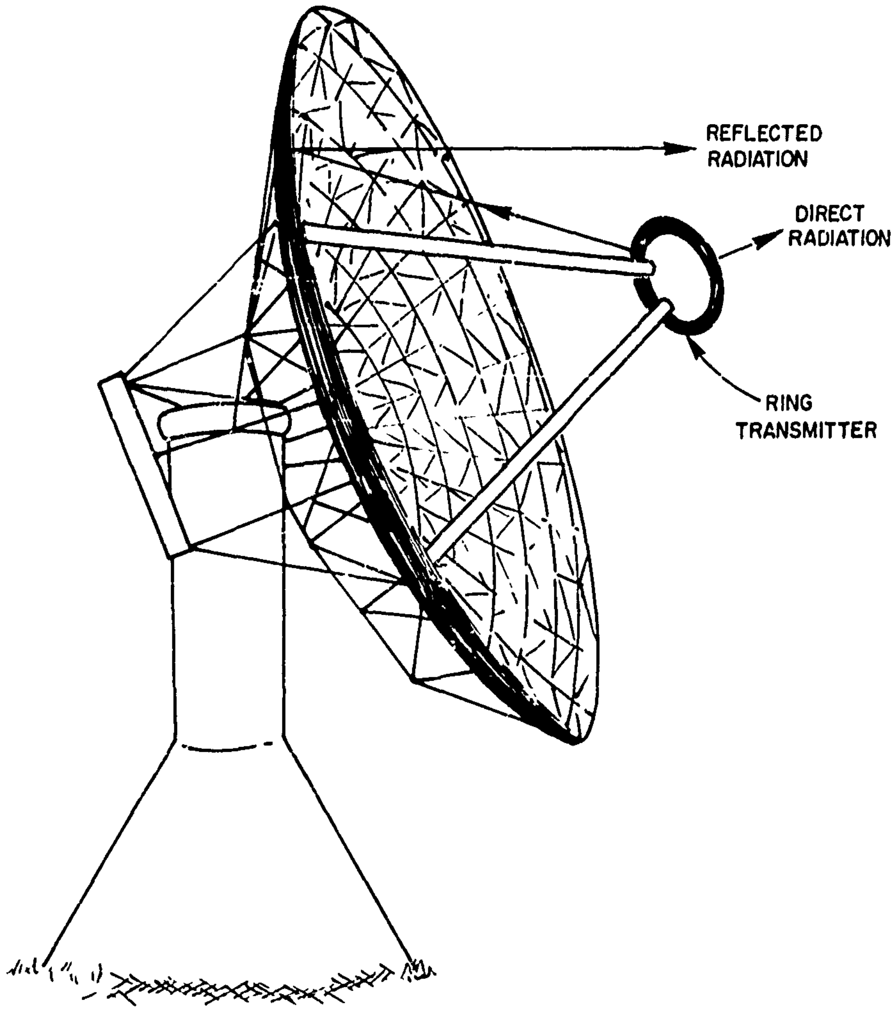

FIG. 32 RING TRANSMITTER AS FEED FOR PARABOLIC DISH

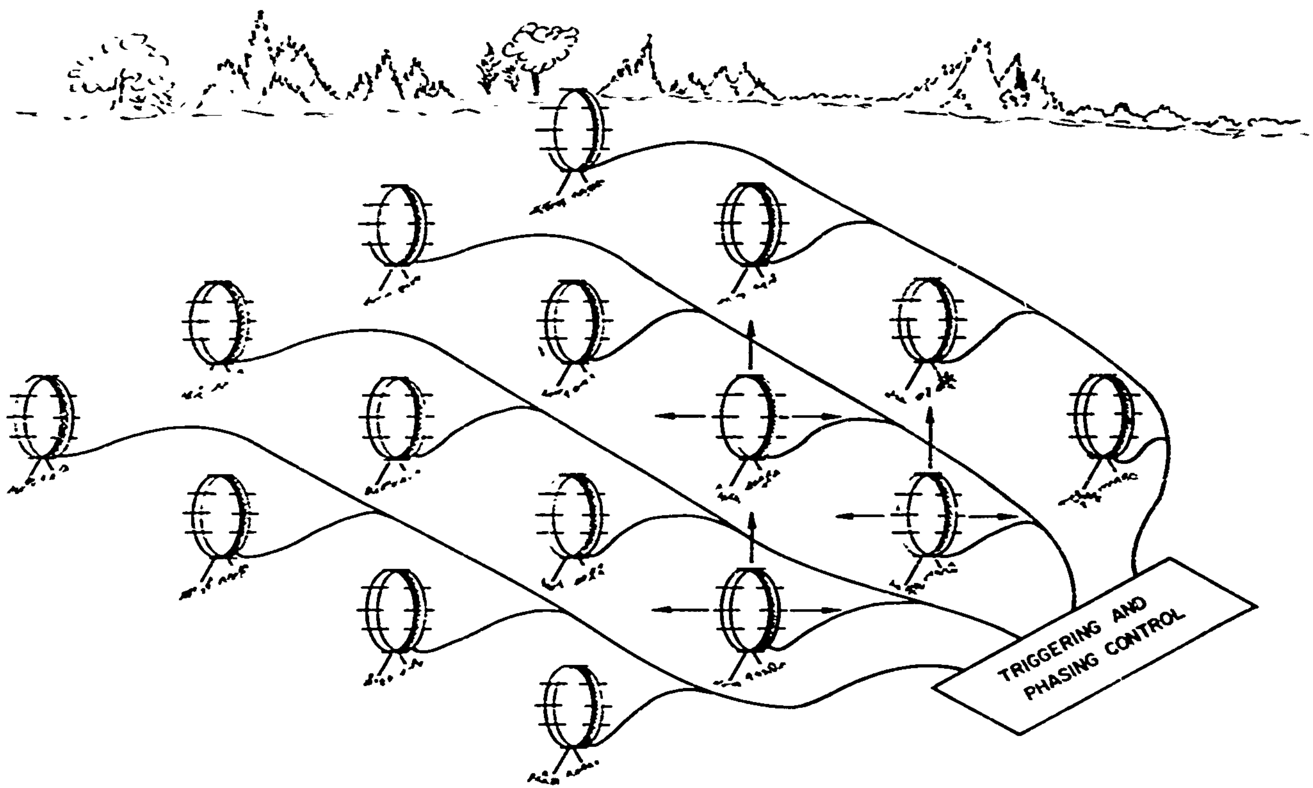

FIG. 33 ACTIVE ARRAY OF RING TRANSMITTERS

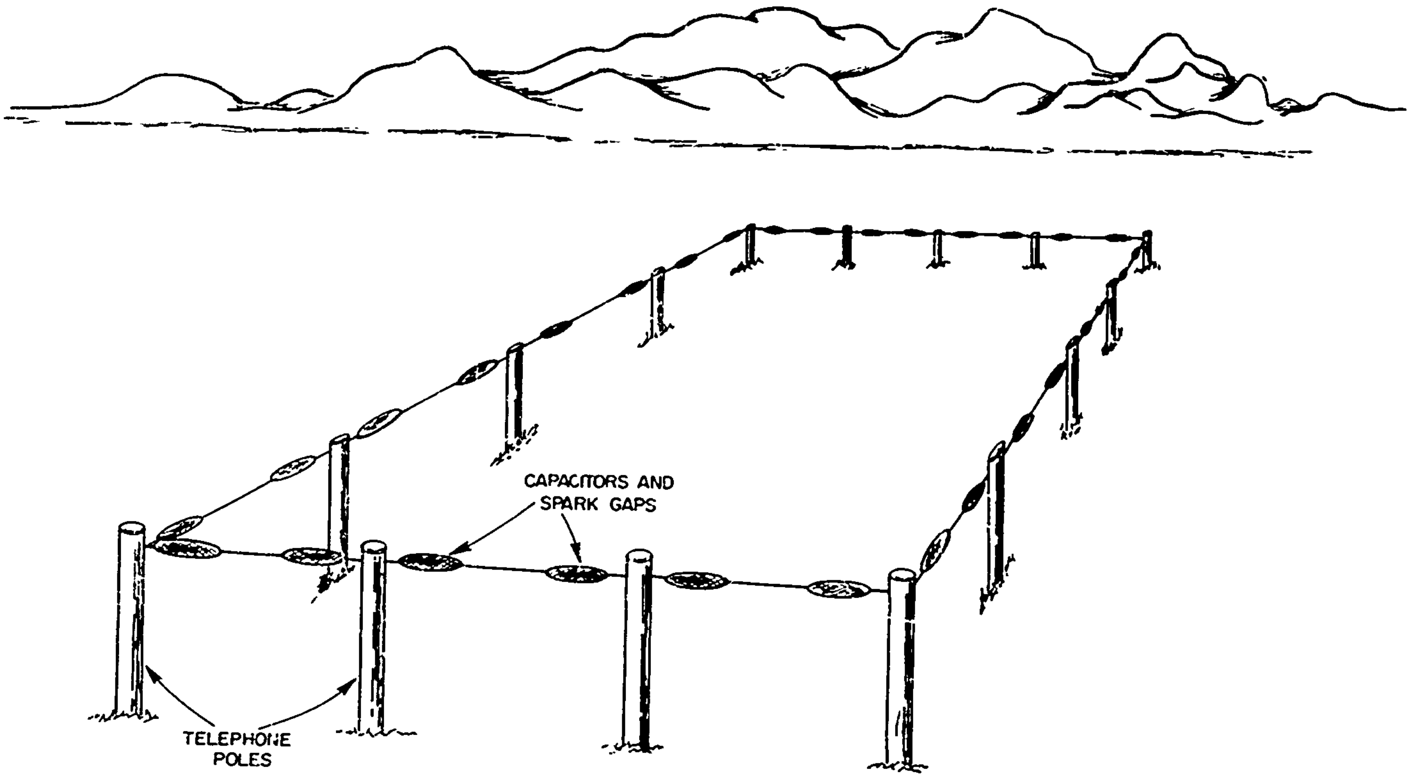

FIG. 34 VLF RING TRANSMITTER

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